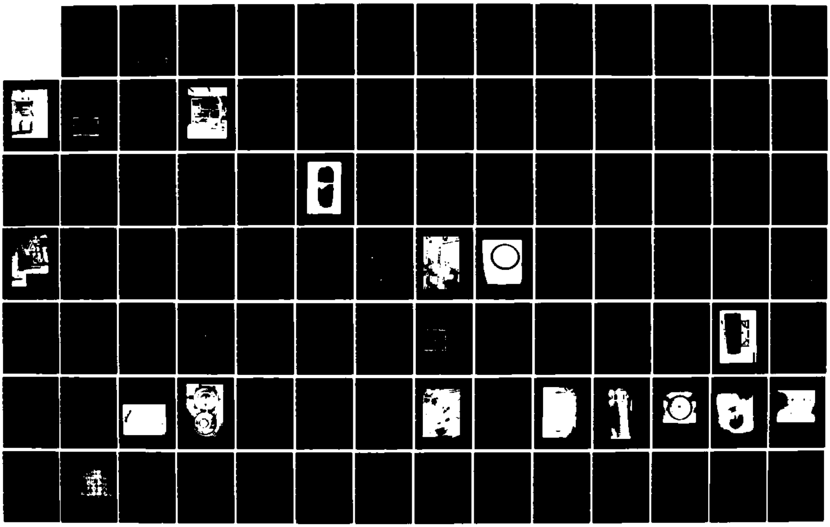
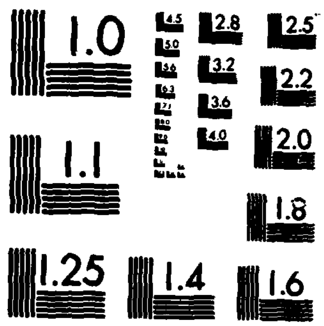
AD-A150 825 AIRCRAFT WING FUEL TANK ENVIRONMENTAL SIMULATOR TESTS 1/2
FOR EVALUATION OF A..(U) BOEING MILITARY AIRPLANE CO
SEATTLE WA P M MCCONNELL ET AL. OCT 84

UNCLASSIFIED DOT/FAA/CT-84/15 DTFA03-83-00038 F/G 13/11 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

②

DOT/FAA/CT-84/15

Aircraft Wing Fuel Tank Environmental Simulator Tests for Evaluation of Antimisting Fuels

AD-A150 825

P. M. McConnell
F. F. Tolle
H. K. Mehta
Boeing Military Airplane Co.
Seattle, WA 98124

October 1984
Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City Airport, N.J. 08405

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/CT-84/15	A150825	

4. Title and Subtitle	5. Report Date
AIRCRAFT WING FUEL TANK ENVIRONMENTAL SIMULATOR TESTS FOR EVALUATION OF ANTIMISTING FUELS	October 1984
	6. Performing Organization Code
7. Author(s) P. M. McConnell, F. F. Tolle, and H. K. Mehta	8. Performing Organization Report No.
9. Performing Organization Name and Address Boeing Military Airplane Company P.O. Box 3707 Seattle, WA 98124	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFA03-83-00038
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405	13. Type of Report and Period Covered Final Sept. 82 - August 84
	14. Sponsoring Agency Code

15. Supplementary Notes

Project Managers', Bruce C. Fenton, H. Stewart Byrnes, Engine Fuel Safety Branch, Aircraft and Airport Systems Technology Division, FAA Technical Center, Atlantic City Airport, NJ 08405

16. Abstract

The low temperature performance of antimisting kerosene (AMK) in airframe fuel systems and in certain engine fuel system components was studied and compared to Jet A fuel. Water vapor ingested into fuel tanks during simulation of repeated descents through clouds and rain had little effect on AMK. AMK retained antimisting properties during exposure to severe environmental flight simulations. Jet pump and boost pump operation had no discernable effect on AMK flammability. Jet pump performance with AMK was adversely affected. Main fuel boost pumps required up to 18 percent more power with AMK than with Jet A, and suction feed performance was lower with ambient and -20°C, but better than Jet A at -40° C. Boost pump performance was not affected by gel formations produced at low temperatures by the vapor removal return flow shearing of AMK. Aerodynamic heating and cooling of AMK in the fuel tank was similar to Jet A. A high pressure pump and needle valve used to degrade the AMK was inadequate, resulting in filter bypass at low temperatures.

17. Key Words	18. Distribution Statement
Antimisting Fuels Aircraft Fuel System Simulation Safety Fuels Fuel System Performance as Low Temperature	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES - (Continued)

LIST OF TABLES

EXECUTIVE SUMMARY

The low temperature heat transfer and fluid dynamic characteristics of antimisting kerosene (AMK) in airplane fuel systems (including a few engine components) were studied by the Boeing Company for the Federal Aviation Administration (FAA). The test program was conducted in the Boeing Fuels Laboratory, North Boeing Field, Seattle, Washington. A 50-gallon cold fuel simulator was used for the environmental simulation and component performance tests. A simulated airplane fuel feed system, designed to evaluate low temperature operation, was assembled for the long term performance (2-hour) tests.

The test results showed that the AMK in the simulator tank retained its antimisting properties

- during exposure to a severe low temperature flight profile with or without slosh and vibration;
- after repeated 6-hour duration thermal cycles between -60°C and 55°C skin temperature;
- after repeated, "worst case" water ingestion simulation runs; and
- during boost pump and jet pump operation.

Gel formations were observed inside the simulator tank during -20°C and -40°C tests with AMK as a result of boost pump vapor discharge jet interaction with AMK during the initial operation of the boost pump. The formations persisted throughout the simulation of the flight, with some gel clinging to the walls. These formations disappeared as the fuel temperature approached ambient and never interfered with boost pump operation.

Anomalous results were obtained from the boost pump power requirements with AMK. Measurements performed during runs with a B747 main boost pump showed that 5 to 18 percent more power was required to pump AMK than Jet A. However, measurements made with an override pump (similar design as the main boost pump) showed the pumping power requirement for Jet A and AMK were approximately equal. For pumps with an increased power requirement, redesign of pump thermal protection provisions would be required.

Jet pump performance was substantially reduced with ambient temperature AMK (compared to Jet A performance) and with -20°C AMK no suction was developed by the pump. However, at -40°C the AMK performance was approximately the same as that for Jet A at the same temperature. This indicates a need to redesign or replace existing aircraft jet pumps.

Generally, suction feed simulation tests with ambient AMK were marginally successful at 30,000 ft and 35,000 ft, and not successful at 40,000 ft, whereas suction feed can be maintained at 40,000 ft with Jet A. This reduction of some 5000 feet would require a similar reduction in airplane service ceiling if not corrected.

An available single pass experimental degrader furnished by the FAA was installed in the system for engine filter performance tests. Filter pressure drops were higher than for Jet A and the filters were more susceptible to plugging as the fuel temperature decreased. At -40°C thick gel formations were observed on the downstream side of the filters and pressure drop data indicated the filters bypassed within a few minutes of operation. Degrader performance must be substantially improved over the test device.

Experience with in-line blending of Jet A and the antimisting additive FM-9™ showed that procedural errors could easily result in fuel/FM-9™ mixtures which formed heavy, difficult to remove deposits on the walls of the containment vessels. This suggests the need for an in-line instrument which could monitor AMK quality at the blender discharge, and could prevent improperly blended fuel from entering the airplane.

1. INTRODUCTION

Simulated airplane impact tests conducted by the FAA have demonstrated that antimisting kerosene (AMK) will prevent the characteristic "fireball" that sometimes occurs following an otherwise survivable crash (references 1 through 4). In low vapor pressure fuels (such as aviation kerosene), fire can be prevented if the high air-fuel shearing action (as fuel spills from ruptured tanks during a crash) can be kept from forming a highly flammable mist. This desired result is achieved by blending a small amount (0.3 percent) of high molecular weight polymer (e.g., FM-9™)* with standard jet kerosene fuel (Jet A), giving the fuel the property of resisting mist formation.

Fuel in this "antimisting" state is susceptible to problems with flowability, especially through filters and other small passages; it also resists the formation of suitable spray patterns in an engine combustion chamber. To restore the flowability of AMK to that of normal jet fuel, and to restore its combustion capability, mechanical shearing or other means of destroying the anti-misting property is required. This degrading process is not planned to occur until the fuel has left the airplane fuel system, and has entered the engine compartment, thereby minimizing the amount of fuel capable of forming flammable mist in a crash.

Since AMK was known to have minor flowability difficulties at ambient temperature it was of interest to find the flow properties of undegraded fuel at low temperature in various airframe fuel system components, and to explore the interaction of cold AMK with water in quantities which might be found in fuel systems. The objectives of this study, then, were to contrast the fluid dynamic, heat transfer and water interaction characteristics of AMK and Jet A in typical fuel system components particularly at low temperature conditions such as are experienced during polar flights; the flammability characteristics of AMK after low temperature exposure in the fuel system were also of interest.

Previous FAA sponsored research on the flow performance and degradation of AMK is reported in the literature (references 5 through 8). These investigations, conducted with fuel ranging in temperature from ambient to approximately $-20^{o}C$, had shown that problems related to flowability, pumpability, gel formation, and water/fuel reactions are generally more pronounced at lower temperatures. Since the in-tank fuel temperatures during a long range, commercial polar flight many reach $-40^{o}C$ or less (reference 9), the scope of the test program included environmental and component performance tests from ambient to $-40^{o}C$ with both Jet A and AMK and a large number of fuel sample characterization tests. Emphasis was placed on finding changes in behavior and/or characteristics of AMK under simulated flight condition extremes and on comparing the performance of fuel system components when using Jet A and AMK fuel.

The primary test articles were a Boeing cold fuel simulator (references 10 through 11) with a capacity of 190 liters, and a simulated airplane fuel feed system which was designed to have many features of the B747 airplane.

It was the desire of the FAA that the performance data with AMK fuel be obtained with fuel freshly produced prior to each test run. The device,

---

*FM-9™ is a proprietary polymer developed by Imperial Chemical Industries (ICI).

developed by the FAA to produce AMK at the test site by mixing Jet A and a polymer slurry (FM-9™), is referred to as an in-line blender. (Previous AMK test data reported in the literature had been obtained with batch blended fuel, prepared several weeks or months prior to the actual test. Relatively large variations in batch blended fuel, either from process variations from batch to batch or resulting from transportation across country have been reported by others (reference 7). It was felt that such problems could be avoided by using in-line blended fuel and that Boeing's experience with the day-to-day use of the blender and with AMK fuel handling would provide valuable field data for the FAA.) At the start of this program, development of the blender was still in progress and had only been satisfactorily demonstrated with a small-scale laboratory model. As the higher capacity, explosion-proof blender with an automated FM-9™ slurry metering pump needed for the tests was not available at the start of the program, early tests were performed with batch blended fuel, but the program soon began using in-line blended fuel. Experience in operating the in-line blender is reported in appendix D for reference to problems encountered and their solutions.

The environmental, component, and boost pump endurance tests were planned to evaluate:

- o differences between AMK and Jet A on a simulated commercial airplane flight using worst case low temperature conditions;
- o the effects of repeated thermal cycles and airframe motion on the antimisting characteristics of AMK;
- o the effects of water/water-vapor ingestion on AMK fuel under "worst case" humidity conditions during flight;
- o AMK performance with production type fuel system components such as a boost pump, engine driven pump, jet pump, and capacitance quantity gauge;
- o the continuous, long time operating performance of a commercial airplane boost pump with cold AMK;
- o the degrading power requirements of AMK at low temperature using an experimental degrader; and
- o the performance of filters typical of an engine fuel feed system with cold AMK over relatively long periods.

These tests are described in detail in the following sections. The test run matrix given in appendix A was extracted from detailed test plans approved by the FAA prior to conducting each test. In each test series, Jet A fuel was used to establish baseline conditions prior to testing with AMK.

2. ENVIRONMENTAL SIMULATION TESTS

Environmental simulation tests included low temperature dynamic flight motion simulation, thermal cycling, and water vapor ingestion tests. These tests were performed in the 190 liter cold fuel simulator tank. A list of test equipment used is given in appendix B.

2.1 Cold Fuel Simulator

Low temperature flights were simulated in a 190-liter (50 gallon) rectangular parallelopiped simulator tank (figure 1) with internal dimensions 51 cm high, 76 cm wide, and 51 cm deep. This simulator has been used in several previous cold fuel investigations (references 10 through 11), and since a detailed

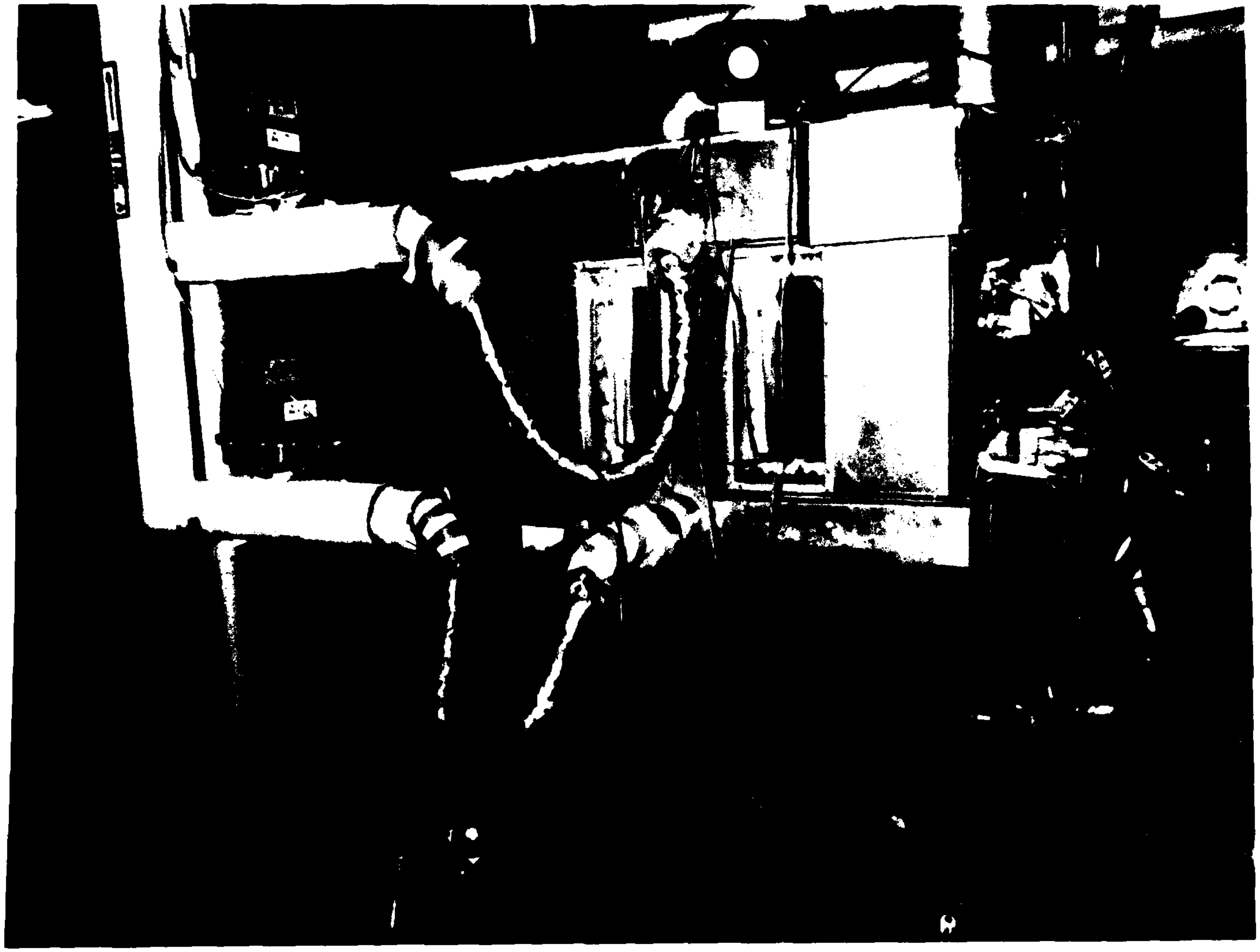


FIGURE 1. COLD FUEL SIMULATOR TEST FACILITY

description of the tank has previously been reported by Byrne (reference 10), only the salient features of the simulator are given here. The tank provides a simulation of heat transfer phenomena which occur during flight in a B747 outboard main tank (4500 gallons). This was accomplished by selecting the depth of the tank approximately the same as that of the airplane wing tank and maintaining the same surface area to volume ratio. This ratio is important since it allows extrapolation of the test results obtained in the simulator to the wing tank without including corrections for geometry differences. Since the heat transfer in a wing tank is predominately through the top and bottom skins, it can be approximated as a one-dimensional process. The simulator tank side walls are insulated to reduce lateral heat transfer, preserving the essentially one-dimensional heat transfer process in a wing tank. The top and bottom walls are constructed of 6061-T6 aluminum having the same nominal thickness as the B747 airplane wing. These walls can either be heated or cooled by a secondary fluid flow. During cooling, the secondary fluid flow temperature was programmed to produce the same skin temperature variation with time as that predicted from analysis of a given flight. The skin temperature control system is capable of tracking a selected time/temperature profile within $\pm 1^{\circ}C$. Continuously varying skin temperature profiles up to 9 hours can be specified in one program (longer times require a second program); in addition, it is possible to hold the skin temperature constant for time periods of any length.

A schematic of the simulator tank is shown in figure 2. The tank contains viewing windows and actual fuel system hardware including a B747 boost pump, stringers, flapper check valves, and is mounted on a slosh and vibration table. The vibration is generated by an eccentric weight vibrator and tank

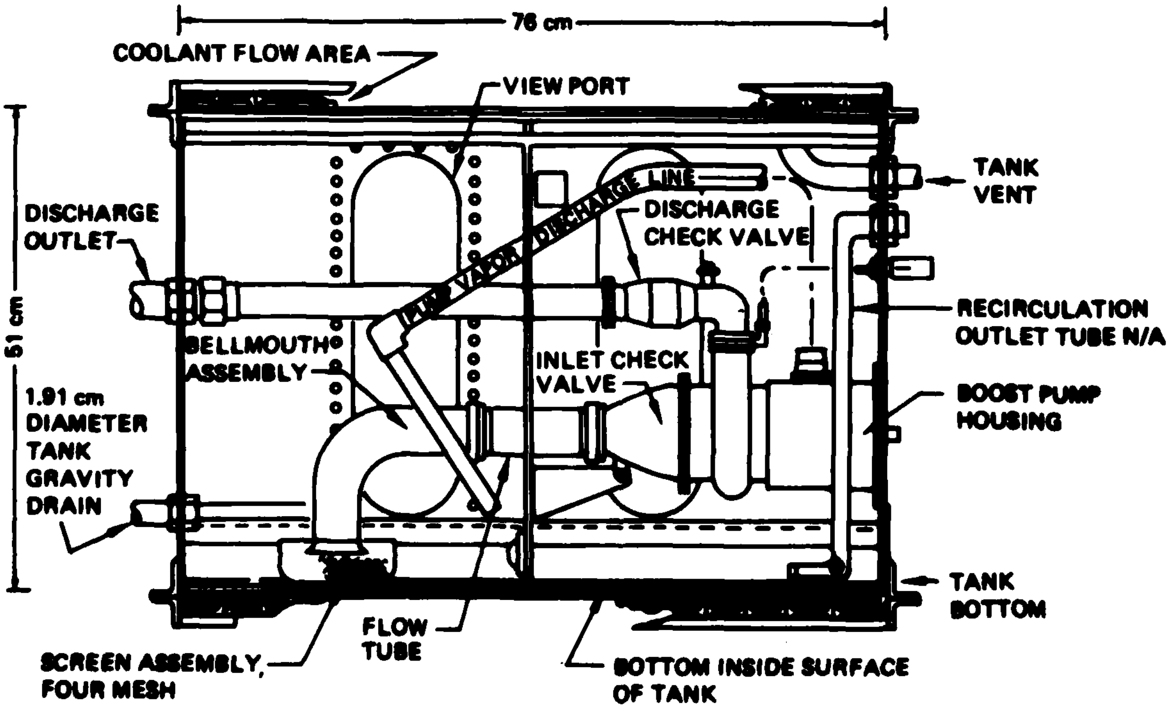


FIGURE 2. INTERIOR OF COLD FUEL SIMULATOR TANK

motion by the slosh table which has a maximum travel of $\pm 15^{o}$ at 0.33 hz. Four accelerometers mounted on the outside of the tank are used to monitor the vibration displacement. Access to the tank, achieved by removing the top of the tank, is a time consuming task because of the heat exchanger plumbing. Therefore, some test configurations were combined to reduce the total number of tank teardowns in the test program. A capacitance type fuel gauge and a jet (water scavenge) pump were added to the simulator tank internal hardware for this program.

The simulator tank instrumentation is summarized in table 1. Temperature, as a function of tank depth, is measured with a vertical array of chromel/alumel thermocouples located near the center of the tank. The array was offset from the mid-point of the tank to avoid interference with a centrally located baffle plate. Thermocouples are also located on the top and bottom inner and outer skins to monitor the skin temperature and to provide feedback to the temperature control system.

TABLE 1. SIMULATOR TANK INSTRUMENTATION

Variable	Range	Instrument	Estimated Measurement Uncertainty
Temperature	$-80^{o}C$ to $80^{o}C$	chromel/alumel thermocouples	$\pm 1.1^{o}C$
Flow Rate	0 to 50 gpm 0 to 10 gpm	turbine meter (calibrated on flow bench)	±1% of reading
Pressure	0 to 20 psig	pressure transducer (strain gauge calibrated with dead weight tester	±0.5 % of full scale
Vibration Displacement and Frequency	0.1 mm	accelerometer (manufacturer's calibration)	± 2% of full scale
Boost Pump Power	0 to 2 Kw	voltmeter and ammeter	±2% of reading
Relative reading Humidity	20% to 90%	humidity sensor (manufacturer's calibration)	±2% of reading
Fuel Weight	0-500 lbs	load cell	±2% of reading

The HP3052A data acquisition system (figure 3) records time, thermocouple output, load cell readings, pressure transducer output, and boost pump power. The data system provides a printed hard copy output for "quick look" and cassette tape, which is converted to a 9-track magnetic tape for subsequent analysis. The maximum scan rate of the system is 20 channels per second and the print rate is 32 characters per second. These rates were adequate for the tests performed in this program.

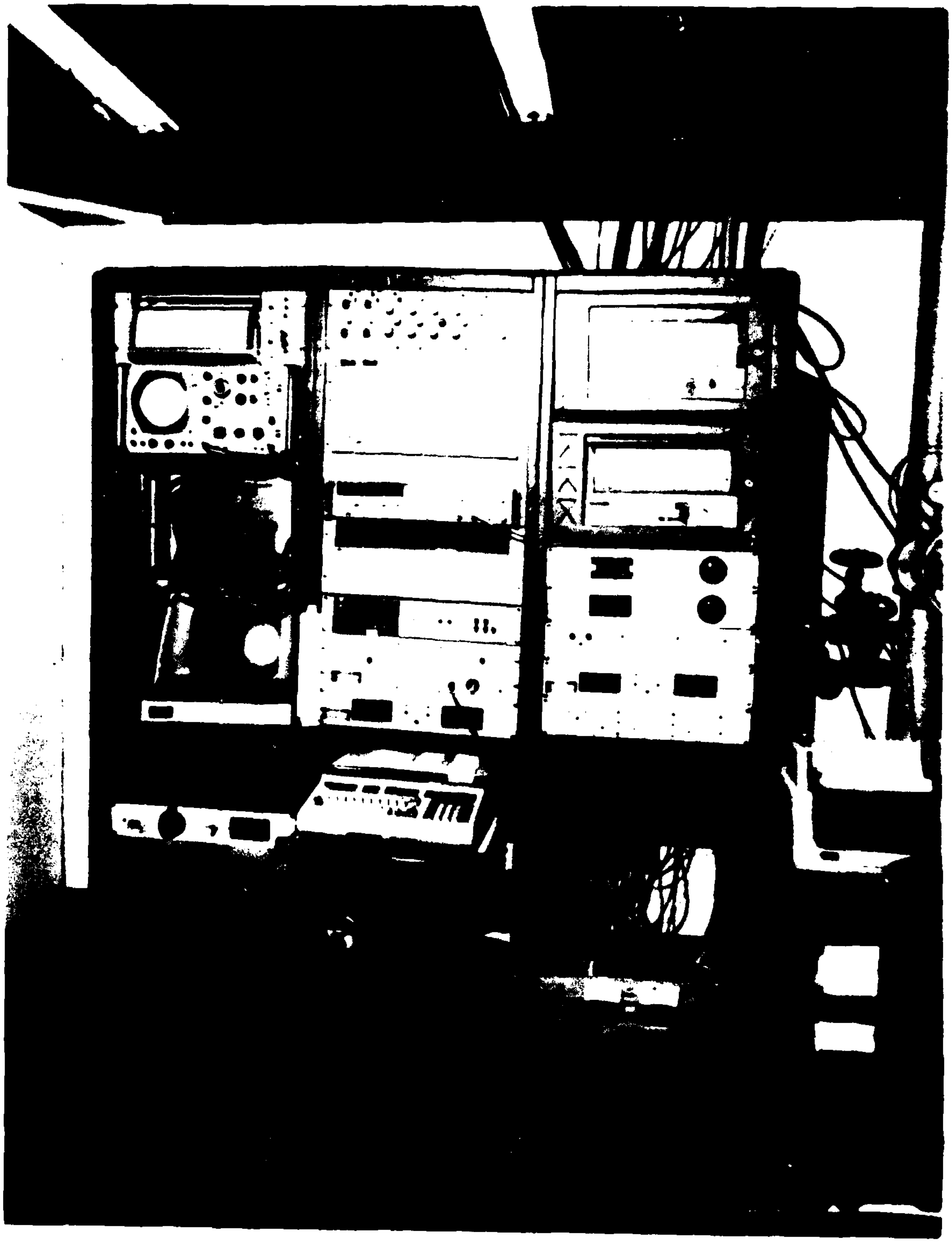


FIGURE 3. DATA ACQUISITION SYSTEM

2.2 Test Fuel

As earlier noted delays in blender development forced the use of batch blended fuel for the environmental tests (low temperature flight simulation, thermal cycling, and water ingestion tests). Four hundred and fifty (450) gallons of batch blended AMK test fuel (0.3 percent FM-9™) were received at Boeing Seattle on 6 April 1983, and later, on 28 April 1983, one hundred and fifty (150) additional gallons were received to complete the remainder of the environmental tests. Rather than using pumps, the AMK fuel was gravity transferred into the simulator tank to minimize handling effects on the test fuel.

The properties of the basestock Jet A from which batch blended AMK was prepared were measured by both Boeing and ICI using procedures as specified in table 2; ASTM procedures are those specified by the letter D and a number. The last three listed tests in table 2 establish flow and flammability properties of the batch blended AMK made from the fuel as tested by ICI at time of preparation, and as received by Boeing.

Data from the orifice cup, filter ratio, and flammability comparison test apparatus (FCTA) indicated that antimisting properties had not been measurably altered during shipment (air freight) or by the time in transit.

Similar procedures were used to characterize in-line blended AMK, and the Jet A from which it was produced. This Jet A was selected to have the highest freeze point (-44°C) available within the specification (-40°C). Samples of AMK were also taken throughout the test series to track and document the physical and flammability properties to compare with the baseline. These samples were characterized according to:

- filter ratio
- orifice cup
- water content
- viscosity ratio (AMK/Jet A)
- flammability
- solids content for in-line blended AMK (D381)

The filter ratio and orifice cup apparatus were provided by the FAA with specific operating instructions. Flammability tests were run on a portable sub-scale FCTA, also provided by the FAA. (Boeing test operators were qualified by the FAA to perform the above characterization test in accordance with FAA procedures.) Results of these fuel characterization tests are included with the individual test results of this report.

2.3 Low Temperature Flight Simulation Test

Low temperature flight simulation tests were performed to evaluate the effects of a "worst case" low temperature commercial airplane flight coupled with airframe dynamics on the antimisting properties of the fuel. Capacitance gauge performance tests were combined with these simulation tests.

TABLE 2. BATCH FUEL CHARACTERISTICS, ENVIRONMENTAL TESTS

Test Description	Procedure	Jet A[1] (FAA Sample)	AMK (FM-9™030)[2] ICI RMH 1-243
Specific gravity @ 60°F	D1298	0.8089	0.8104
Viscosity @ 60°F (centistokes)	D445	2.14	3.51
Freeze Point (°C)	D2386	-44	-43
Reid Vapor Pressure @ 100°F (lb)	D323	0.7	0.3
Water Content (PPM)	D1744	31	15
Thermal Conductivity @ 32°F (Btu/Hr - °F - ft)	D2717	0.0733	0.0754
Hydrocarbon Types, FIA (%V/V)	D1319		
Saturates		83.0	-
Olefins		0.8	-
Aromatics		16.2	-
Hydrocarbon Fractions (PONA)			
Saturates (Paraffins and Napthalenes)		83.8[3]	-
Olefins		0.2	-
Aromatics		16.0	-
Orifice Cup	FAA		2.4, 2.5
Filter Ratio	FAA		82.6
FCTA	FAA		

1 Jet A fuel used by ICI to produce batch blended AMK

2 Boeing measurements on as received fuel

3 The separation of the saturates fraction into paraffins and naphthenes is ambiguous. The data indicate that the saturates fraction contained approximately 45 percent paraffins and 55 percent naphthenes.

2.3.1 Worst Case Flight Profile Identification

The worst case low temperature exposure of fuel in an airplane was determined from an analysis of actual commercial polar routes. Polar routes were selected because they present the most severe thermal exposures for city pairs of interest (reference 9). It was stipulated by the FAA that at least one of the cities of the candidate routes be located in the United States. In this study, the candidate routes were winnowed down to two for detailed examination. These were: Helsinki-Seattle (10 hour flight) and New York-Tokyo (13 hour flight), with route coordinates given in table 3. Route

TABLE 3. COMMERCIAL POLAR ROUTES CONSIDERED FOR COLD FUEL HEAT TRANSFER ANALYSIS

Route Description	Latitude	Longitude	Altitude (Ft)	Cummulative Distance (nM)	True Air Speed (Kts)	Mach No.
New York-Tokyo	40.38N	75 W	39,000	0	481.8	0.84
(33.0 Knot Head Wind)	56.45N	89.45W	39,000	1150		
13 Hours	68.15N	124.05W	39,000	2300		
	67.04N	173.34W	39,000	3400		
	67.04N	173.34W	39,000	4600		
	53.42N	155.17E	39,000	5844	481.8	0.84
	35.46N	140.23E				
Helsinki-Seattle	60.19N	24.37E	35,000	0	484.2	
(22 Knot Head Wind)	66.48N	54.60W	35,000	850	484.2	
10 hours	73.10N	43.50W	35,000	1700	484.2	0.84
	71.56N	74.29W	35,000	2550	484.2	
	59.17N	111.02W	35,000	3400	484.2	
	47.27N	122.18W	35,000	4214	484.2	

variables (latitude, longitude, altitude, airspeed) were input to the Boeing TEC 153 computer program. This program, designed to find the day on which the most severe low temperature exposure occurs for a given airplane route in the northern hemisphere, was used to study both the above routes. The data base for this analysis is 10 years of meterological data (1966-1975) containing two records per day for each of seven altitudes at each of 1977 points in the northern hemisphere; these data were acquired from the National Center for Atmospheric Research, Boulder, Colorado. Data for each of the twice daily records is scanned by interpolating position, altitude, and Mach number along the route of flight. The output from TEC 153 is a time averaged route temperature and a data file containing time-temperature variation for the 15 worst cases (based on a ranking of the minimum time averaged temperature for each day studied). Plots of the 15 worst cases for the two study routes are given in figures 4 and 5, with the solid curve in each figure being the worst of the 15 cases.

The validity of this approach has recently been confirmed by comparison of actual in-flight skin temperature data with calculations performed for the same day and route. (Reference 12) In general, the difference between the calculated and actual route temperature was less than 3°C.

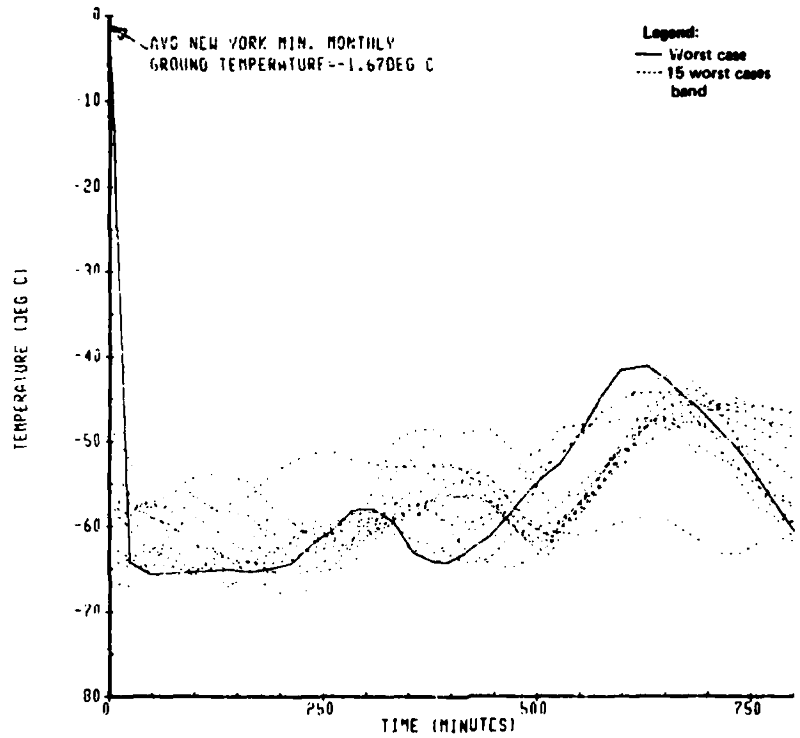


FIGURE 4. PREDICTED EXTREME, LOW-TEMPERATURES, NEW YORK TO TOKYO POLAR ROUTE

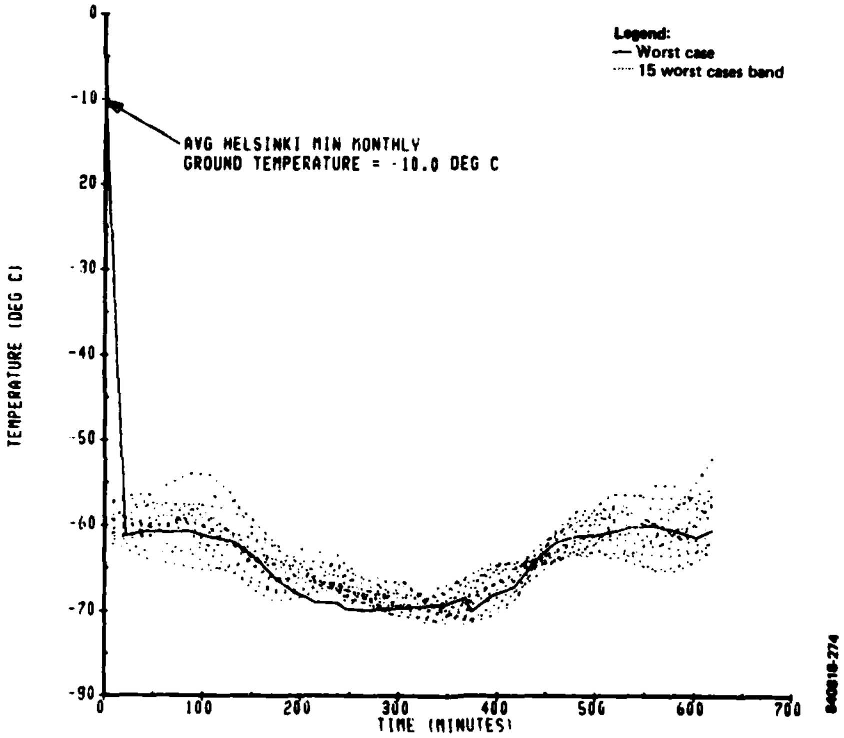


FIGURE 5. PREDICTED EXTREME LOW-TEMPERATURES, HELSINKI TO SEATTLE POLAR ROUTE

The takeoff point in each city pair was based on the lower temperature at either airport. New York and Helsinki were chosen on the basis of lowest monthly mean ground temperatures (table 4).

TABLE 4. MEAN MINIMUM GROUND TEMPERATURE AT TAKEOFF POINTS FOR WORST CASE LOW TEMPERATURE FLIGHTS

	Jan	Feb	Mar	Dec
Helsinki	17^oF (-8.3^oC)	14^oF (-10.0^oC)	19^oF (-7.2^oC)	21^oF (-6.1^oC)
New York	27^oF (12.8^oC)	28^oF (-2.2^oC)	32^oF (0.0^oC)	29^oF (-1.67^oC)

2.3.2 Time Varying Skin Temperature Calculation

For purposes of heat transfer calculations, ambient temperatures along the routes were converted to recovery temperatures using the usual relationship

$$T_R = T_\omega \left(1.0 + \frac{\gamma-1}{2} R M_\omega^2\right), \tag{1}$$

where,

T_R = recovery temperature
T_ω = ambient temperature
γ = C_p/C_v (1.4 air)
R = recovery factor ($\sim$ 0.9)
M_ω = free stream Mach number ($\sim$ 0.84)

Plots of the ambient and recovery temperatures for the most severe day for each route are shown in figures 6 and 7. Both routes experience essentially the same minimum temperature for about three hours. However, the bulk fuel temperature will be lower in the Helsinki-Seattle flight than the New York-Tokyo flight because: the initial fuel temperature is 8.3^oC lower, the minimum temperature experienced during the flight occurs later in the flight profile; and the time-averaged temperature is lower. Therefore, the Helsinki-Seattle route was identified as the worst case and selected for simulation.

In-tank temperature variation and skin temperature for the Helsinki - Seattle polar route were next calculated with a one dimensional combined conduction convection thermal analysis program. (Reference 13) Nominal fuel properties of Jet A were assumed for the analysis. The initial (takeoff) bulk fuel temperature for the analysis was assumed to be equal to the average minimum Helsinki February ground temperature (-10.0^oC). Plots of temperature versus fuel tank height predicted from this program are given in figure 8a and b. Free convection heat transfer and mixing are responsible for the uniform temperature region at the top of the tank while the steep thermal gradient at the bottom is typical of the conduction heat transfer process which dominates this region. The average heat transfer coefficient at the tank top varies with the tank Rayleigh number from approximately 20 Btu/^oF-ft^2 to zero as

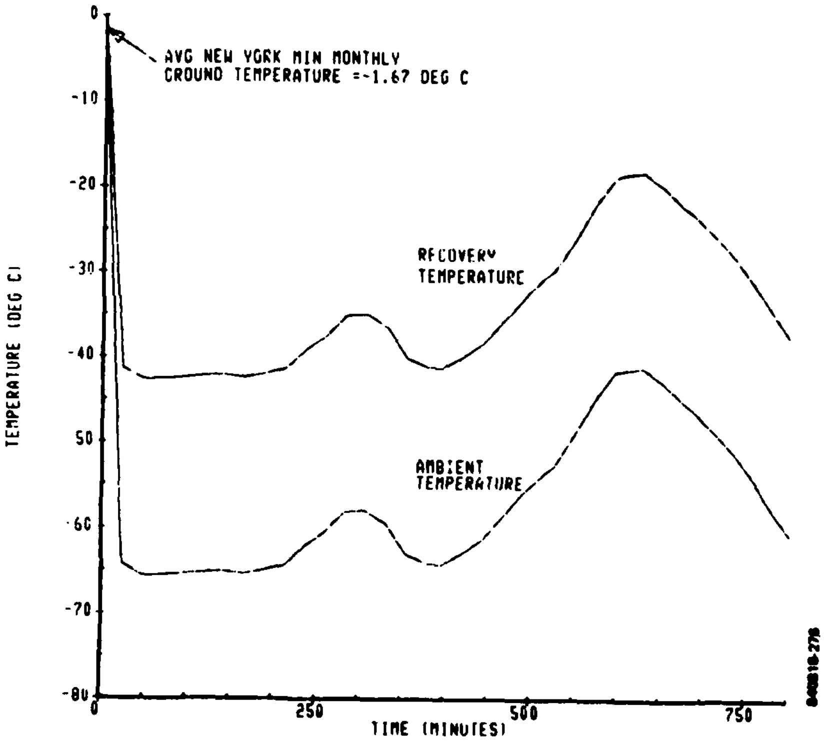


FIGURE 6. PREDICTED WORST CASE AMBIENT AND RECOVERY TEMPERATURES, NEW YORK TO TOKYO POLAR ROUTE

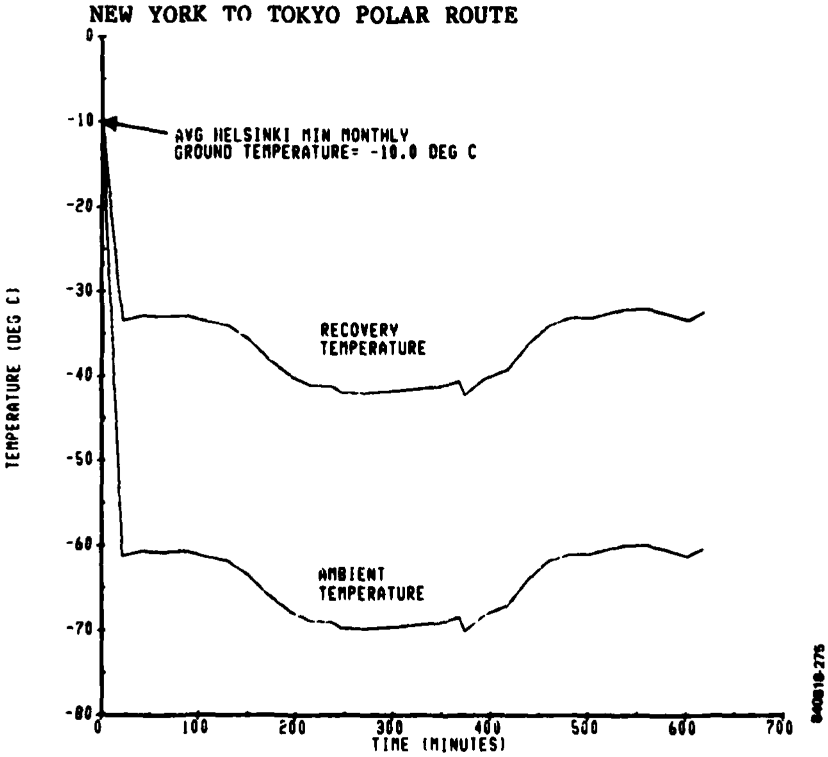


FIGURE 7. PREDICTED WORST CASE LOW-TEMPERATURE FLIGHT, HELSINKI TO SEATTLE POLAR ROUTE

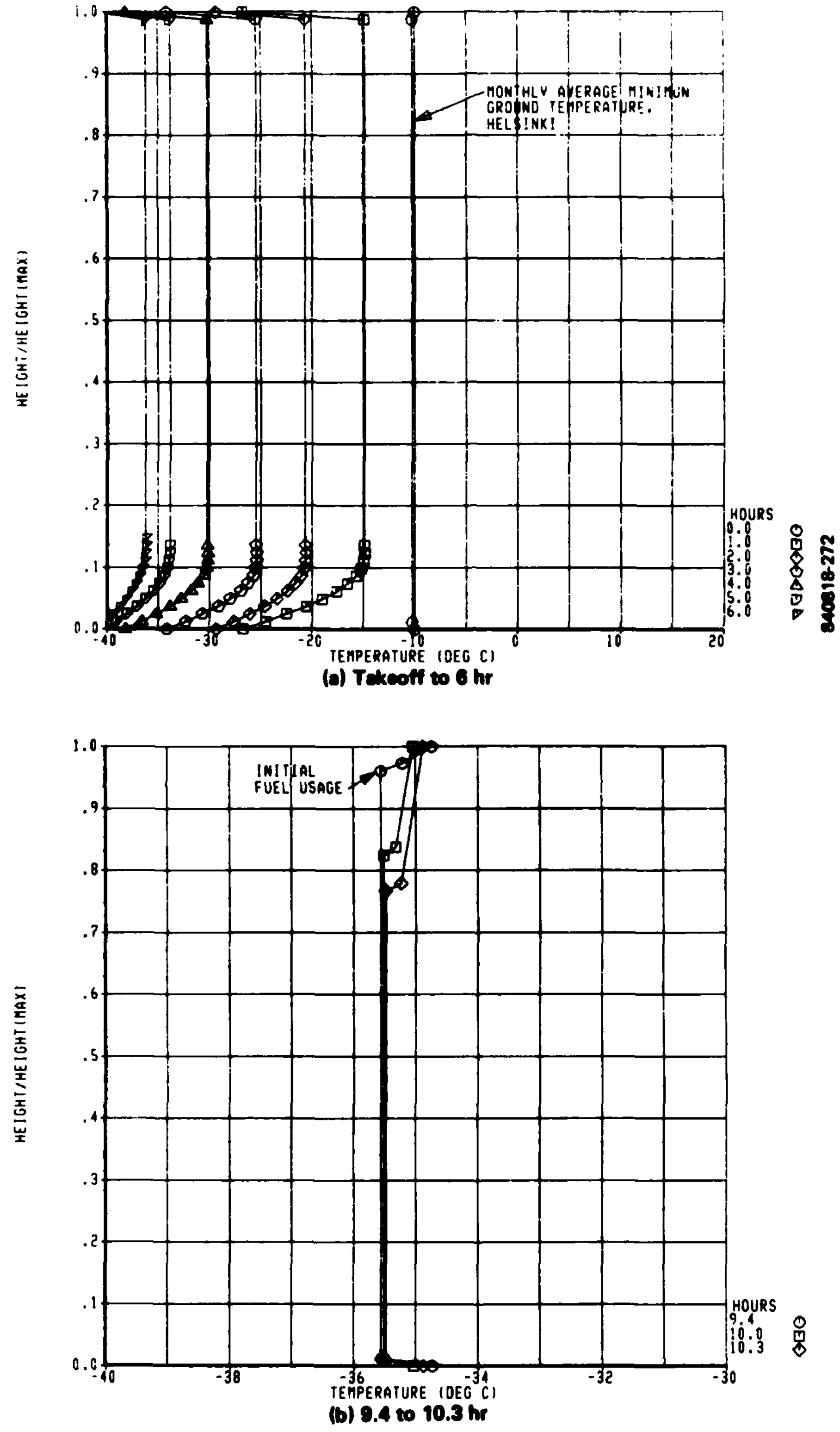


FIGURE 8. CALCULATED FUEL TEMPERATURES-HELSINKI TO SEATTLE

the fuel cools down. Figure 9 shows the predicted skin temperature and bulk temperature versus time during the worst case flight. The minimum predicted bulk fuel temperature, -37.5°C, occurs at approximately 7.3 hours and the minimum skin temperature, -41.3°C, occurs at 6.4 hours. No fuel freezing would be predicted from these profiles since the freeze point of the Jet A test fuel is approximately -44°C.

The above temperature calculations were performed for a full tank. The dihedral of the wing causes the inner upper skin to be wetted by fuel and the outer upper skin to be dry. Hence, the full simulator tank best models the inboard section of a nearly full airplane wing tank. Because of the convective heat transfer which results when the upper skin is in contact with the liquid, the bulk fuel temperature will decrease much more rapidly when the tank is full than when the tank is partially full.

Near the end of the flight, fuel warming during descent occurs at about the same time that fuel consumption causes the upper skin to lose contact with the fuel. Under these conditions the shape of the thermal profiles tends to reverse because of a free convection region which develops at the bottom of the tank.

2.3.3 Dynamic Simulation

Tank motion resulting from air turbulence, uncoordinated airplane maneuvers, and the dominant engine vibration frequency (53 Hz) were simulated during the test. The simulated gust magnitude and frequency and maneuver cycles (figure 10) were obtained from in-flight measurements, and are typical of large transport airplanes. Previous cold fuel tests have shown that slosh and vibration enhances the heat transfer process and the fuel cooling will proceed more rapidly than with no induced motion.

2.3.4 Test Procedure (Runs 1 through 3 and 5 through 7)

In the low temperature/dynamic tests, the selected Helsinki - Seattle flight was simulated by controlling tank skin temperatures, slosh and vibration, and the fuel withdrawal rate. Fuel tank pressure altitude was not simulated in this series of tests. The calculated skin temperature (figure 9) was programmed into the test tank temperature controller prior to the test; fuel temperature was next dropped to -10°C, after which the flight simulaton was begun. Six runs were performed in this test series: runs 1 to 3 using Jet A for establishing baseline conditions (ambient, -20°C and -40°C) and runs 5 to 7 using AMK.

As mentioned earlier, the experimental simulation was performed with a full tank. To compensate for thermal contraction of the fuel during cooling, a 3-gallon reservoir mounted above the simulator was used to maintain liquid contact with the top skin during the 10-hour simulation. At the end of the flight, the fuel level was gradually reduced by intermittent operation of the boost pump, using approximately 10 pulses every 2 minutes (figure 11).

Fuel samples taken from the simulator tank at specified times during the tests were used to evaluate the effects of the simulation on AMK characteristics. To avoid degrading the AMK it was important to obtain samples with minimum flow shear and agitation; a rule of thumb developed was that the local velocity to diameter ratio should be less than 200. When drawing cold fuel

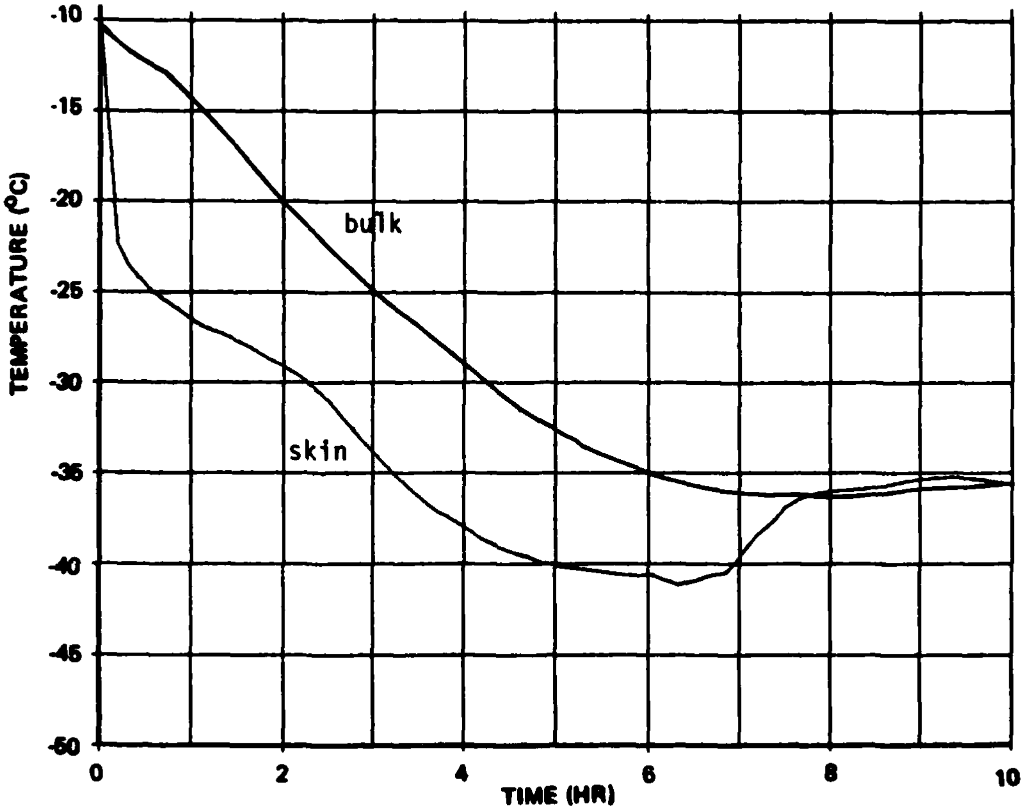


FIGURE 9. PREDICTED IN-TANK SKIN TEMPERATURE AND BULK TEMPERATURE HISTORIES, HELSINKI TO SEATTLE, JET A FUEL

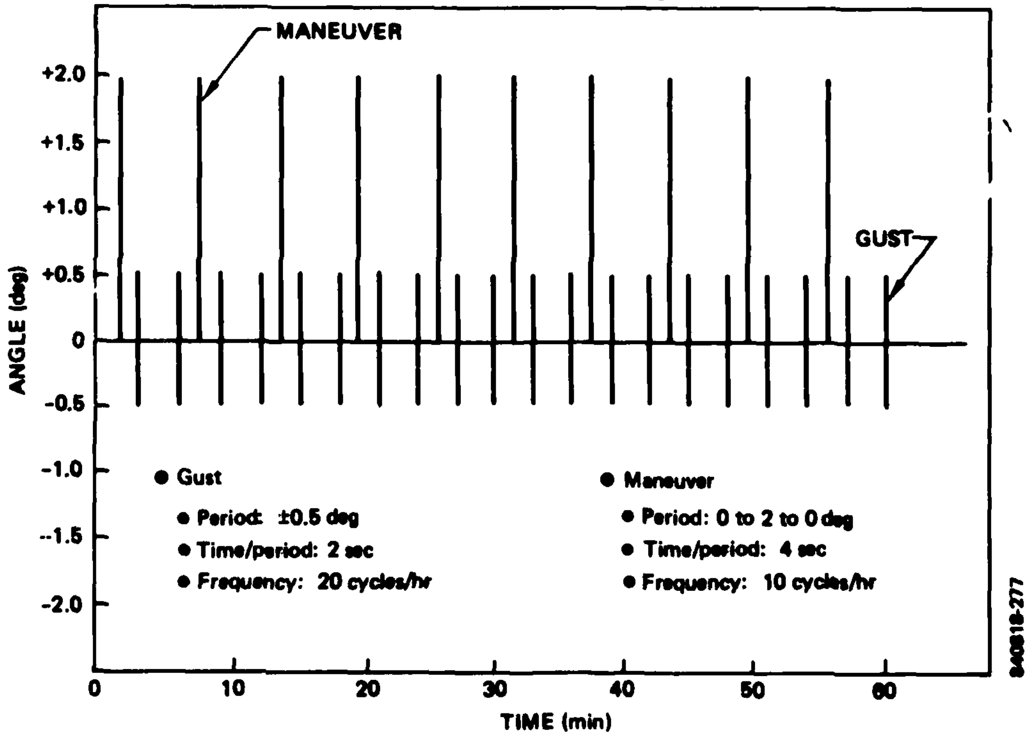


FIGURE 10. SIMULATED GUST AND MANEUVER CYCLES

samples, it was necessary to prevent introducing extraneous amounts of moisture into the sample. This was accomplished by using a transparent, flexible tube, 1-inch diameter and approximately 6 ft long, connected to the drain line at the bottom of the simulator tank with two ball-valves (figure 12). During the test, both valves were closed with end B elevated above the top of the tank, as shown. When a sample was to be collected, valve A was opened first. The pour spout (end B) was inserted into a 2 gallon sample container (aluminum can) after which valve B was opened. The container was then slowly lowered until approximately 1-3/4 gallons of fuel were collected, at which time valve A was closed. The fuel remaining in the line between valves A and B was then allowed to drain into the container for a total sample volume of 2 gallons. Valve B was then closed and end B raised to its original position. To avoid condensing water from the moist air in the sample container, the sample can was purged with dry nitrogen gas prior to sampling. Immediately after a sample was taken the sample can was tightly capped and labeled.

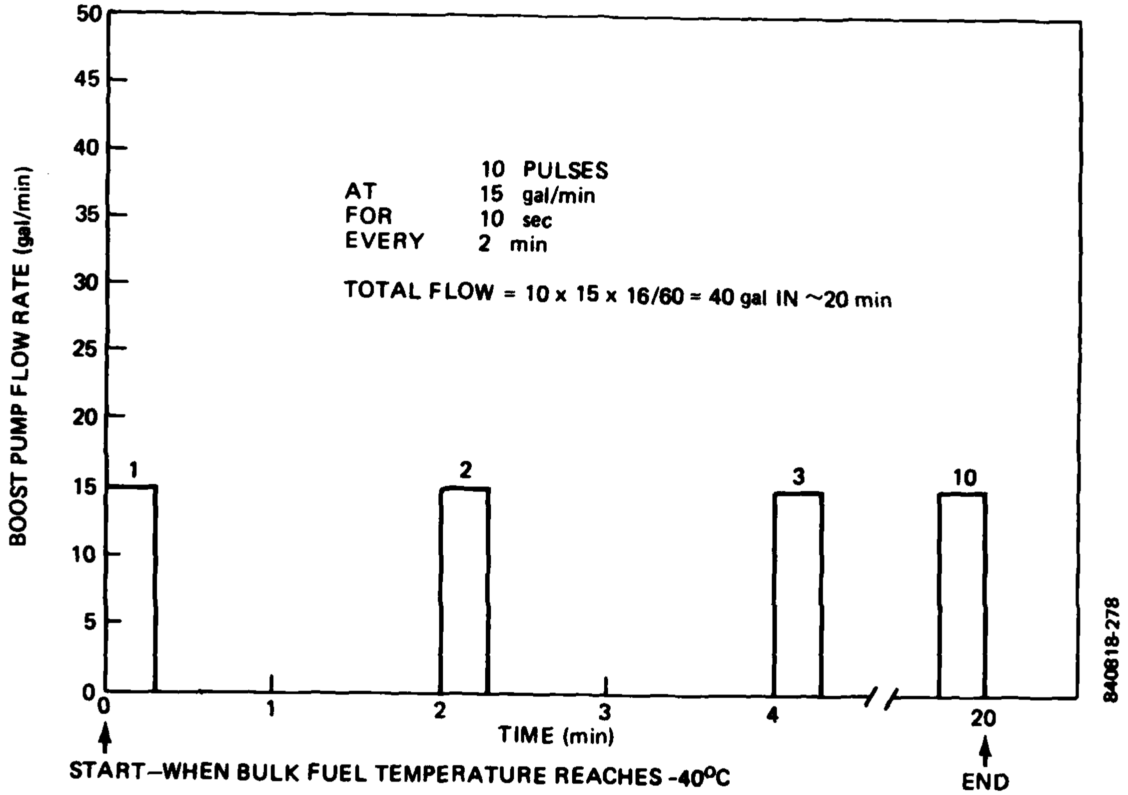


FIGURE 11. BOOST PUMP OPERATING TIMES FOR LOW-TEMPERATURF/ DYNAMIC TEST SERIES

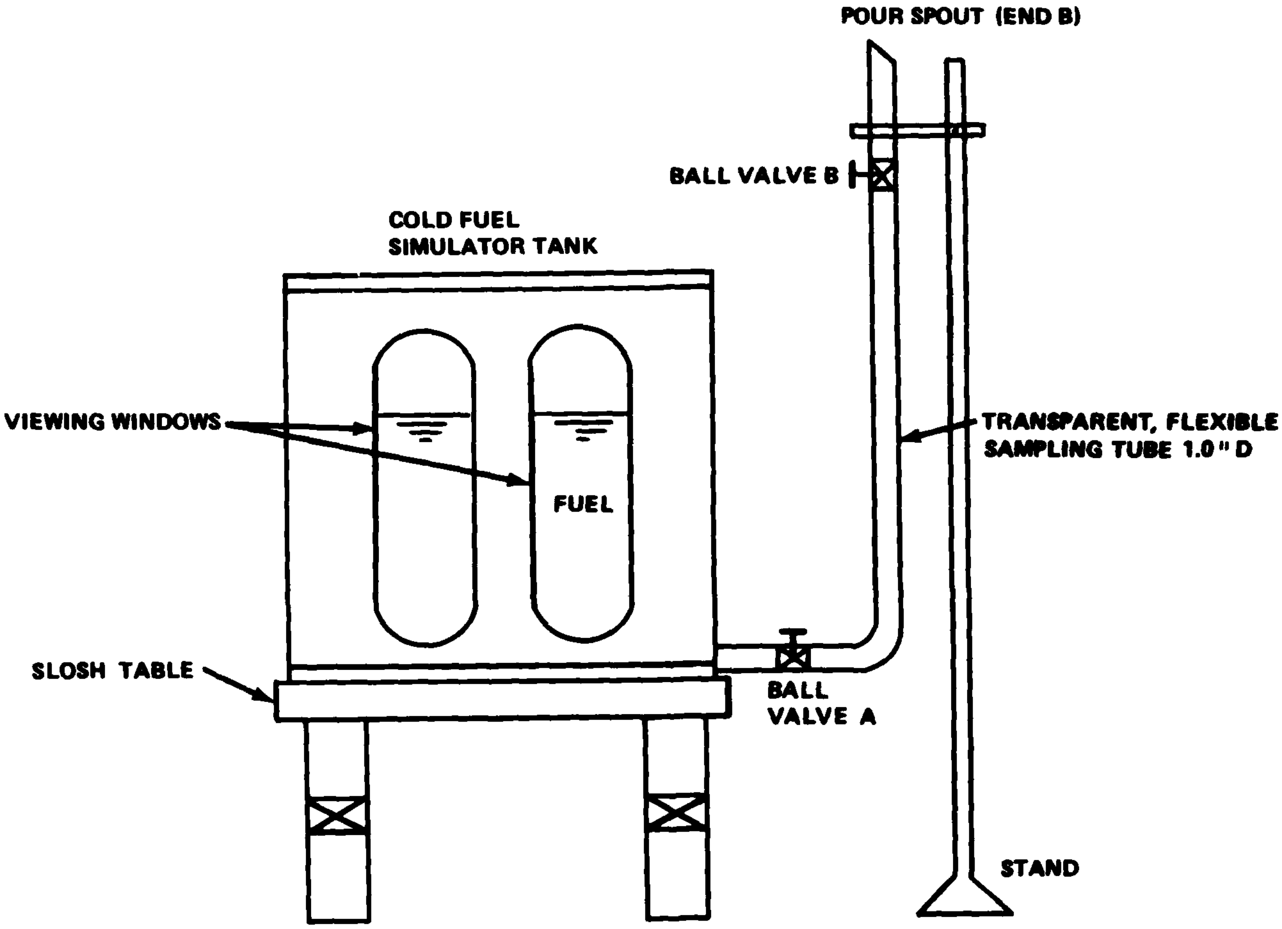


FIGURE 12. AMK FUEL SAMPLING ARRANGEMENT

2.3.5 Results

The calculated and measured skin temperature and bulk fuel temperature histories of the simulation with Jet A are plotted in figure 13. As predicted, minimum fuel temperatures were higher than the fuel freeze point, and no fuel freezing was observed in the tests. Measured temperature distributions in the tank are plotted as a function of time in figure 14a and 14b. These profiles (generally the same for Jet A and AMK) have the same shape as those predicted and are generally within $\pm 2^{\circ}C$ of the predicted values at the same times.

Comparison of the bulk fuel cooldown rate with AMK and Jet A (figure 15) shows no major differences in the thermal response between the two fuels. However, some interesting observations during the AMK low temperature dynamic tests are:

- o At ambient temperature, AMK in the test tank is clear (same as Jet A). However, the AMK fuel generally remained clear even at $-40^{\circ}C$, in contrast to the typical dark yellow (opaque) appearance of Jet A at this temperature.

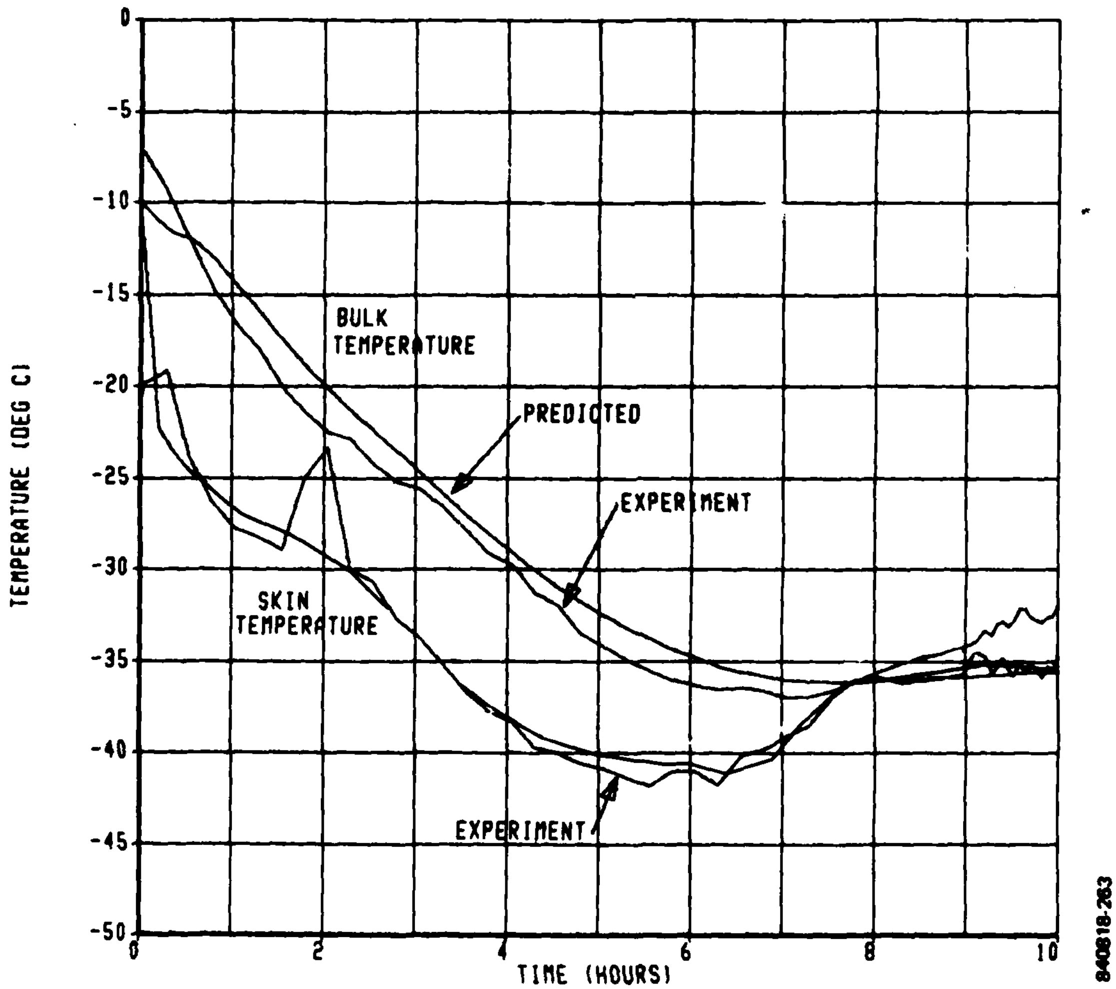


FIGURE 13. COMPARISON OF EXPERIMENTAL AND PREDICTED TEMPERATURES, JET A

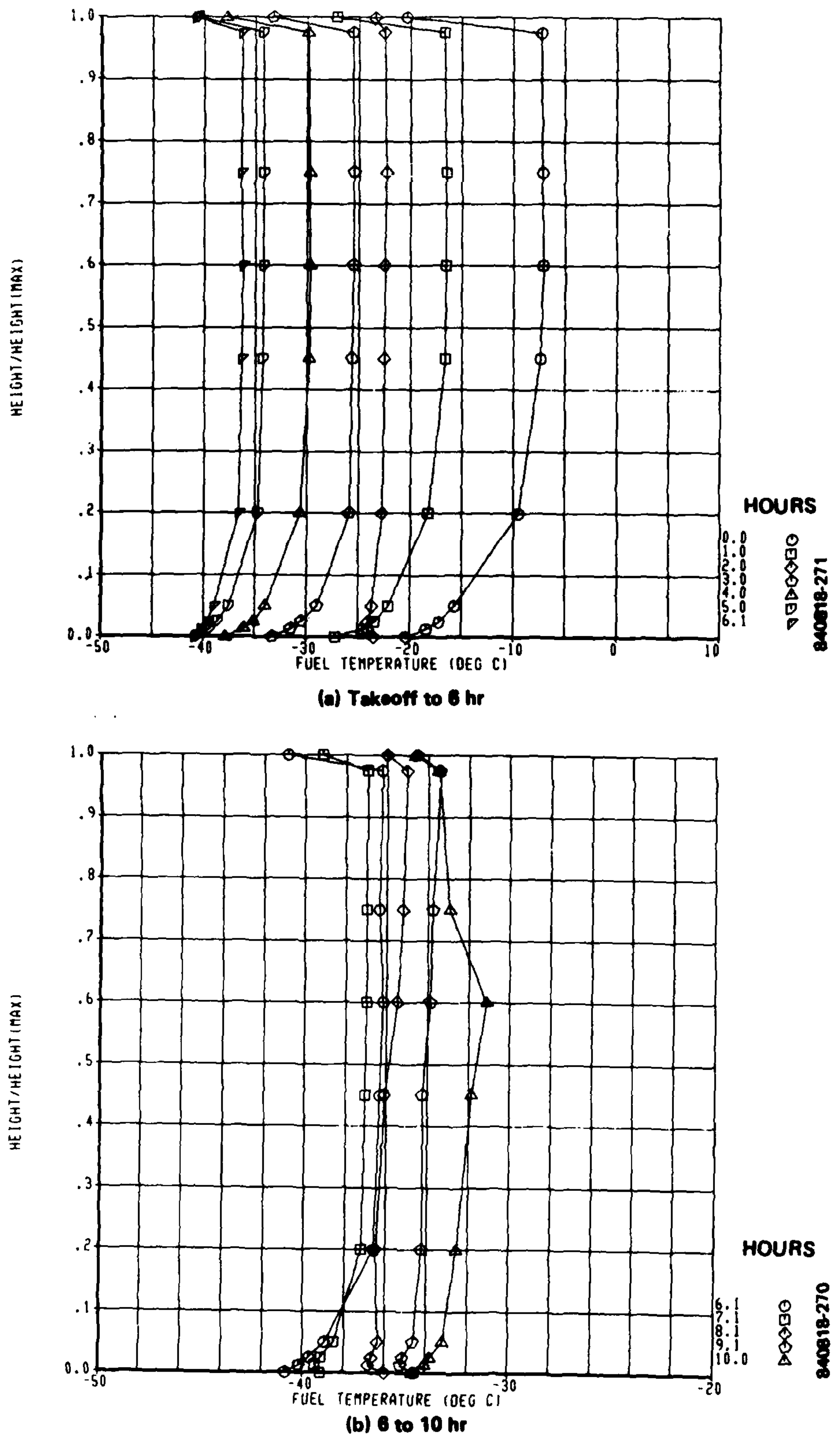


FIGURE 14. MEASURED TEMPERATURE PROFILES, JET A

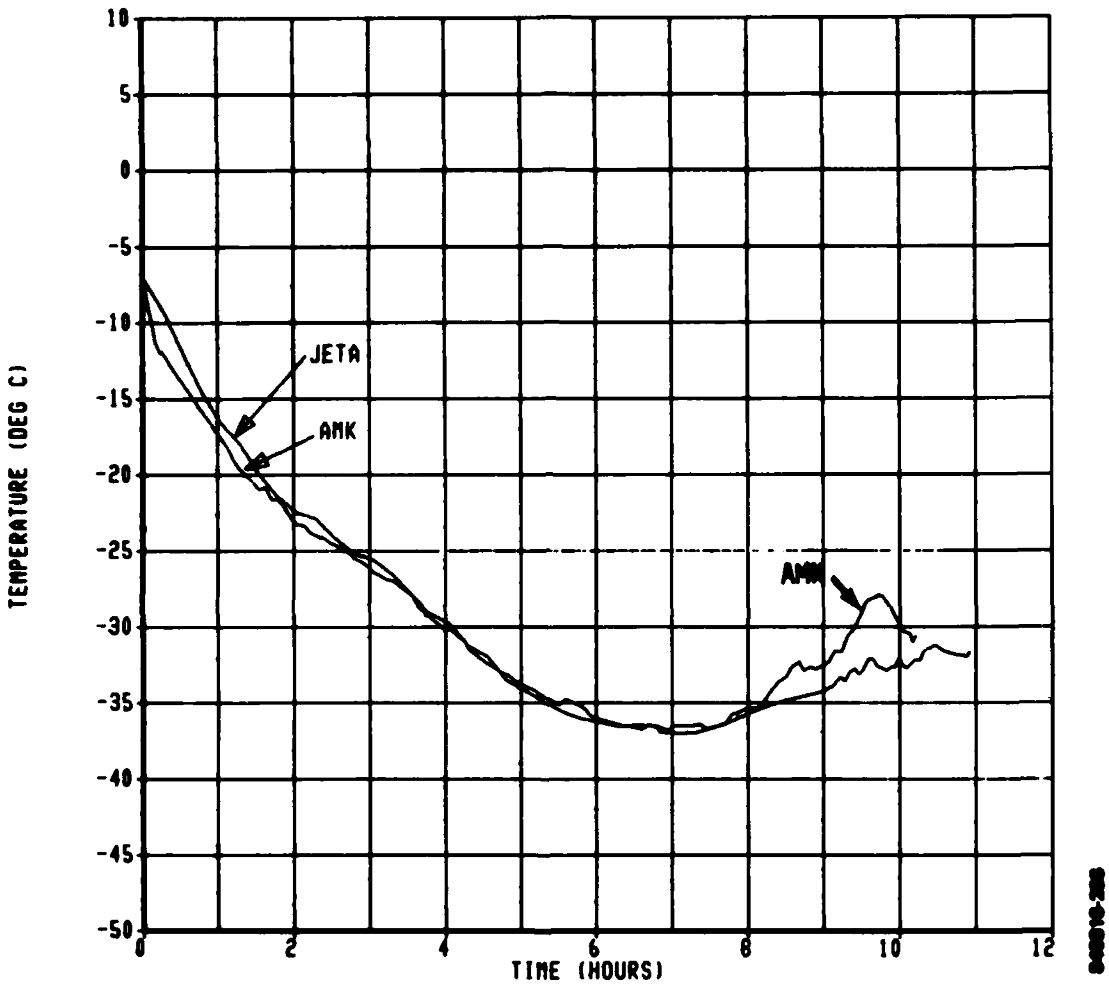


FIGURE 15. COMPARISON OF EXPERIMENTAL BULK TEMPERATURES, JET A AND AMK

- During boost pump operation, strands of a gel-like, semi-transparent material were observed on the free surface of the fuel and interior surfaces of the tank; figure 16 shows a typical formation. The formation of the gel is believed to be a result of agitation of the cold fuel by the boost pump vapor removal flow (approximately 5 gpm) which was discharged into the suction side of the test tank in these tests. The gel persisted until the conclusion of the test run at which time the fuel temperature was approximately -28°C. As the fuel warmed overnight, these formations disappeared and no deposits remained on the tank walls or internal surfaces by the next morning. In a repeated test run when fuel was cooled to -20°C and the boost pump operated continuously for one minute, the gel was again observed but after approximately 15 minutes had dissolved back into the fuel. Motion pictures were taken of the gel formations and sent to the FAA as part of the original data package.

2.4 Thermal Cycling Test

Thermal cycling tests were performed to determine the effect of repeated thermal cycles and airframe dynamics on the antimisting characteristics of AMK. The tests were designed to simulate fuel in a seldom used (reserve) tank which could therefore experience a number of flight cycles before being used.

2.4.1 Description of Test

The AMK was cycled over the extreme skin temperature range of -60°C to 55°C for five consecutive cycles without attempt to duplicate a flight cycle. A typical cycle is shown in figure 17. The initial cooldown profile starting from ambient temperature was the same as that used in the low temperature dynamic tests. These temperatures represent extreme values which would probably never be encountered during any present day commercial routes. The fuel was subjected to repeated freezing and thawing during this series of tests, since at -60°C the fuel is in a nonflowable (frozen) state. The thermal cycles were repeated on succeeding days for a maximum of five cycles. Samples of fuel were withdrawn after each cycle and analyzed to determine the effects of the exposure.

Observations of the fuel during these tests are summarized as follows:

- When the bulk fuel temperature (indicated by the thermocouple located 10 cm from the bottom skin) fell below about -24°C, the fuel became slightly cloudy although visibility in the tank was still good. Below -45°C the first frozen fuel accumulations were observed on the bottom and top skins of the tank. These accumulations tended to build up at approximately 0.15 inch/min at the bottom, and at a lesser rate at the top skin. When slosh was initiated, the slurry was observed to respond to the tank dynamics. This response stopped as the fuel became colder, and around -46°C, the fuel behaved as a solid. At the completion of the 3-hour cold soak with skin temperature at -60°C, the bulk temperature was -48°C and all of the fuel in the tank appeared frozen solid.

- During the heating cycle, the formation of "strings" (transparent gel) was observed as the bulk fuel temperature passed through the temperature range from -23°C to -4°C. The first string formations

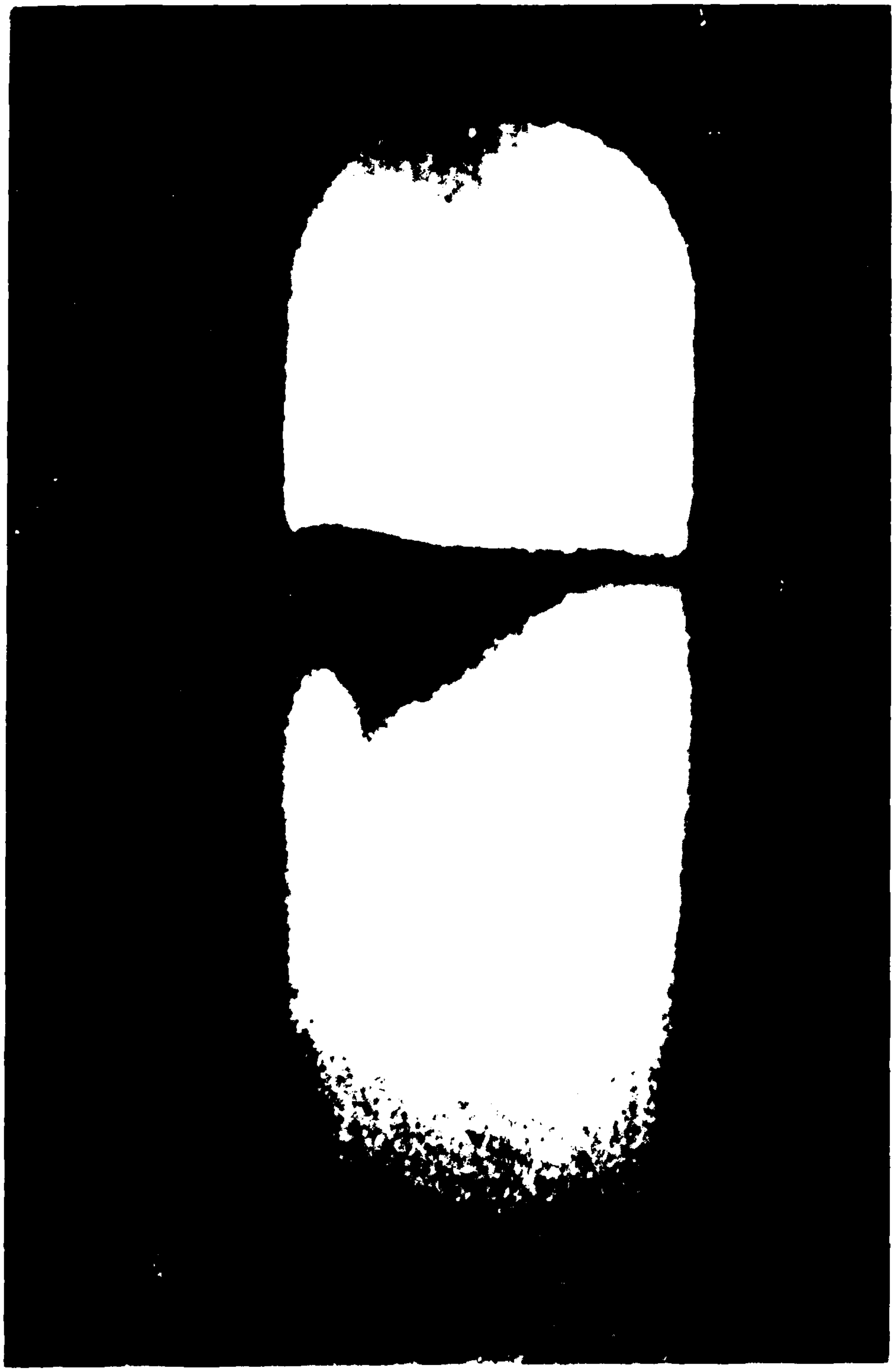


FIGURE 16. GEL FORMATIONS OBSERVED DURING BOOST PUMP OPERATION IN SIMULATOR TANK

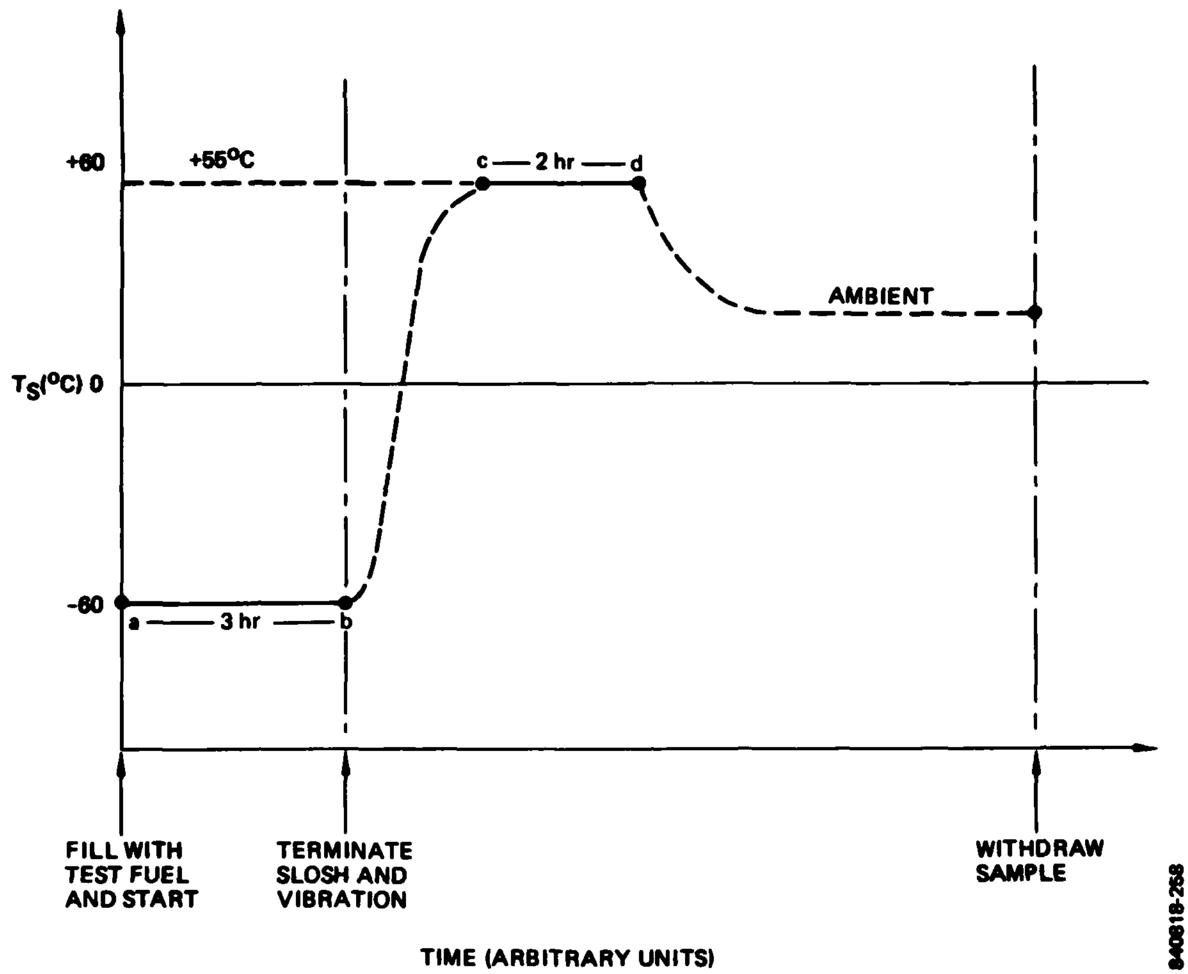


FIGURE 17. THERMAL CYCLE PROFILE USED IN ENVIRONMENTAL TESTS

appeared near the top skin/fuel interface. As the temperature increased, the strings increased in number and detached from the top of the tank and due to convective motion were distributed throughout the fuel. At about -4°C the strings disappeared. Motion pictures of these phenomena (which were observed during all five cycles) clearly show the strings. However, the strings did not show up in still photographs taken during these tests probably because of their transparent nature.

- In the 2nd cycle, the fuel color was slightly darker (yellowish-brown color) at the low temperatures, but freezing phenomenon was about the same as before. At ambient temperature the fuel returned to the color of normal Jet A.

- In the 3rd, 4th, and 5th cycles, the fuel was much darker at low temperatures and freezing could no longer be observed clearly. Again, at ambient temperature the fuel color appeared normal (same as Jet A).

o Visual inspection of the fuel tank after the tank was drained showed no deposits on the interior surfaces.

2.4.2 Results

Results of the AMK samples taken from the drain line at the bottom of the simulator tank during the tests are reported in table 5. The data show a tendency for the orifice cup flow rate to increase and the filter ratio to decrease with repeated cycling, however, the repeatability of this trend was not demonstrated; the FCTA tests showed that the fuel retained its flammability protection during all cycles.

TABLE 5. SUMMARY OF AMK CHARACTERISTICS, RUNS 8-12.

		Orifice Cup*		Filter Ratio		Viscosity (CS)		Water Content (PPM)	
No.	Description	Pre-Run	Post-Run	Pre-Run	Post-Run	Pre-Run	Post-Run	Pre-Run	Post-Run
8	Thermal Cycle 1	2.6,2.6	2.5,2.6	90.9	64.3	3.47	3.45	43	75
9	Thermal Cycle 2		2.9,2.8		56.9		3.43		76
10	Thermal Cycle 3		2.6,2.7		57.3		3.42		69
11	Thermal Cycle 4		2.7,2.7		46.7		3.39		73
12	Thermal Cycle 5		3.0,3.0		40.5		3.39		82
-	Baseline AMK (as received)			81.6,77.6, 78.7					
-	Distilled Water		8.8,8.8						
-	Jet A		8.2,8.2						

* Orifice cup results are reported in units of milliliters of fuel which flow through the orifice in 30 seconds.

2.5 Liquid Water/Water Vapor Tests

The interaction of water vapor and water droplets with cold AMK is a major concern in the development of a successsful antimisting fuel. Previous research on water reactions with AMK had shown that precipitates formed when water vapor came into contact with cold AMK (reference 3 and 14). In these studies, the amount of water ingested into the fuel tank represents an extreme case, and was much greater than the amount expected to be ingested into the fuel tanks during most flights.

The objectives of the water/water vapor tests were to determine: if airborne water introduced into the fuel tank ullage through the vent system during descent through a region of extreme high humidity (rainstorm) combined with slosh and vibration would subsequently condense and react with the antimisting agent; and to evaluate the effect of water and airplane motion on the antimisting properties of the fuel.

2.5.1 Analysis of Water Vapor Ingestion During Worst Case Conditions

The most realistic simulation would be obtained with a vent system that added air at the worst case pressure, temperature and humidity conditions which would be found in a descent through a rainstorm. Simulations of the several variables simultaneously have been found to be extremely difficult to control accurately in simulations. Therefore, some simplifications were considered necessary.

The worst case situation is considered to be an airplane descending from cruise altitude 12,000 m (40,000 ft) to sea level through clouds with heavy rain, such as might be encountered in a tropical or sub-tropical warm front. To achieve a pressure balance on the tank during descent, atmospheric air containing water vapor and water droplets flows through the fuel tank vent system. Since the vent entrance either faces down or aft, the larger liquid droplets are not likely to be ingested, and 100 percent humidity air plus fine suspended droplets is a likely worst case for vent system water ingestion. However, it is not clear what happens to the water as the supersaturated air passes through the vent system and enters the tank ullage. Fuel temperature, fuel depth, tank shape, tank wall temperatures, and the vent system design are all variables which might lead to condensation forming in the vent system lines as well as in the fuel tank ullage. With cold aircraft structure and cold fuel in the tank, water would be expected to condense (and possibly freeze) on all cold surfaces.

The mass of water ingested into the tank during the time of descent is

$$m_w = \int \left(\frac{dm_{H_2O}}{dt}\right) dt \qquad (2)$$

with some manipulation, the integral can be converted to one over altitude

$$m_w = \int_{40,000'}^{o} \frac{\dot{m}(h)\ w(h)}{\rho(h)\dot{h}}\ dh, \qquad (3)$$

where $\dot{m}$ = mass flow rate of air into the ullage
ρ = air density
w = water density
$\dot{h}$ = descent rate
dh = altitude

Assuming that the ullage volume remains constant (very low fuel-flow rate) during the descent and that the perfect gas law applies, Equation (3) can be transformed into the following form:

$$m_w = \frac{V}{R} \int_{40,000'}^{o} c(h) \cdot \left(\frac{1}{T}\frac{dp}{dh} - \frac{p}{T^2}\frac{dT}{dh}\right) dh, \qquad (4)$$

where, V = ullage volume
$c(h)$ = concentration of water at height h (vapor + fine mist)

p = absolute pressure
R = gas constant
T = absolute temperature

Maximum water vapor concentrations used in the calculation were those reported by Grantham and Sissenwine (reference 15) and for cloud precipatate concentrations (fine mist) by Sissenwine and Cormier (reference 16). The integration of equation (4) was performed numerically in 1000-ft increments (40 steps), using average values of each variable within each step. The outboard main tank volume of a B747 is 567 ft^3 (4250 gal). With an 80 percent ullage (454 ft^3) the calculated mass of ingested water is 0.42 pounds, which is approximately one cup of water per 3400 gallons. Scaling to the 50-gallon test tank (40 gal ullage) gives 2.2 ml of water or 92 PPM. The ingestion would take place over a 40-minute period, which approximates the time of descent from 40,000 feet.

2.5.2 Water Ingestion Test Procedure (Runs 4, 13-16).

The tests were started with a full tank of AMK test fuel. The tests were performed initially with batch blended AMK and were repeated later in the program with in-line blended AMK; one water vapor ingestion test, run 4, was conducted with Jet A fuel for comparison purposes. The cruise phase of the flight was simulated until the bulk fuel temperature reached -40^{o}C. At this point, 80 percent of the fuel was withdrawn and the tank evacuated to simulate a 40,000 ft pressure altitude, the nominal assumed condition at the end of cruise (prior to descent). A typical simulated descent pressure profile is shown in figure 18. During the descent period the tank vacuum pump was turned off to avoid removal of any ingested water vapor.

The water ingestion tests required a specified volume of water (2.2 ml) to be vaporized and mixed with dry air and then to be drawn into the evacuated ullage of the test tank during the simulated descent. A small boiler, comprised of a 2-inch diameter, 12-inch long stainless steel tube with a copper steam line brazed along the bottom (figure 19) was used to convert the water into vapor. The specified 2.2 ml of water was injected by syringe through a sealed penetration into a pre-heated copper holding cup located inside the 1-inch tube, as shown. The water vapor, entrained and mixed with dry air, was bled into the tank during the simulated descent. A schematic of the test set-up and instrumentation is shown in figure 20. A humidity probe, located at the downstream end of the boiler, measured the humidity of the mixture leaving the boiler. This probe, selected because of its size, response time, and cost, came factory calibrated over the 20 percent to 90 percent range of relative humidities. It was anticipated that the probe response would indicate 100 percent relative humidity since the air was expected to be supersaturated with water at the point of measurement.

During the actual ingestion simulation it became apparent that a continuous, controlled pressure increase over a 40-minute period simultaneous with water vapor ingestion was more difficult than anticipated. Therefore, the ingestion was performed in a series of three steps (0.73 ml of water per step). Between steps, dry airflow was stopped and the tank allowed to gain pressure very slowly (approximately 0.01 psi/min) by air seepage inherent in the system. Motion pictures (64 frames per second) were taken during each of the ingestion cycles and were reviewed after the tests were completed.

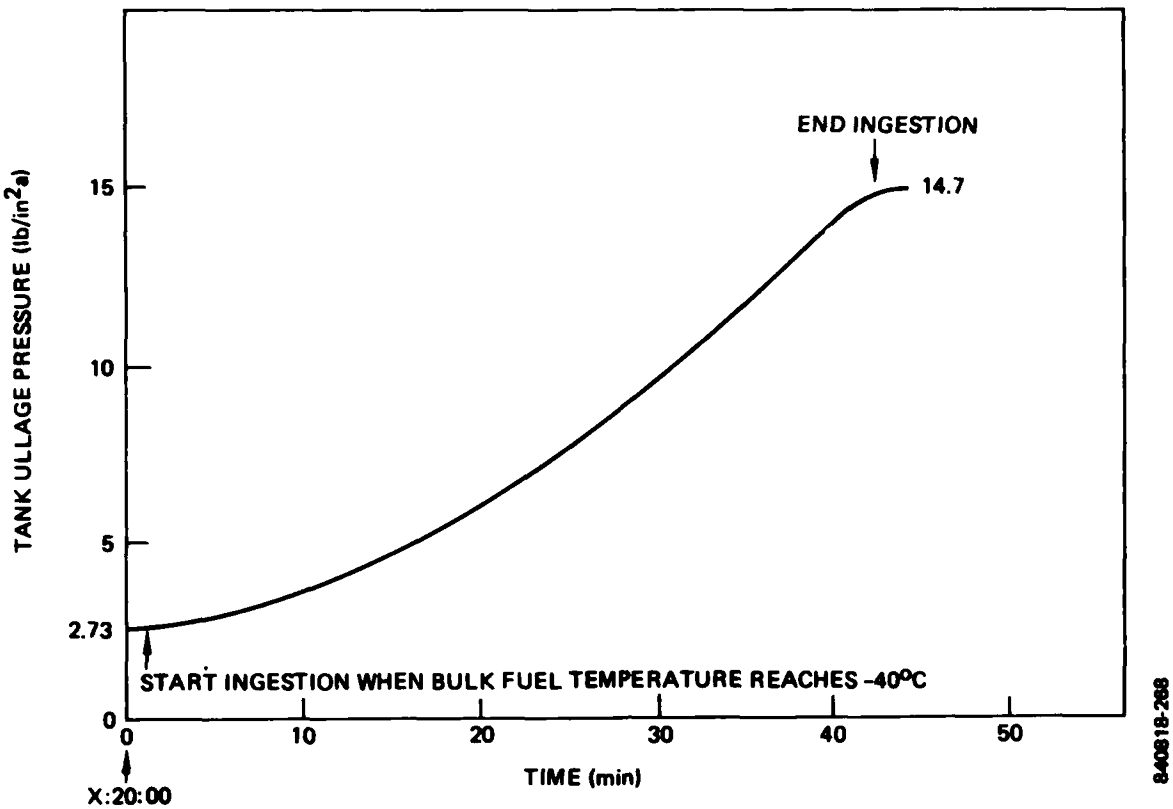


FIGURE 18. WATER VAPOR INGESTION PRESSURE SCHEDULE

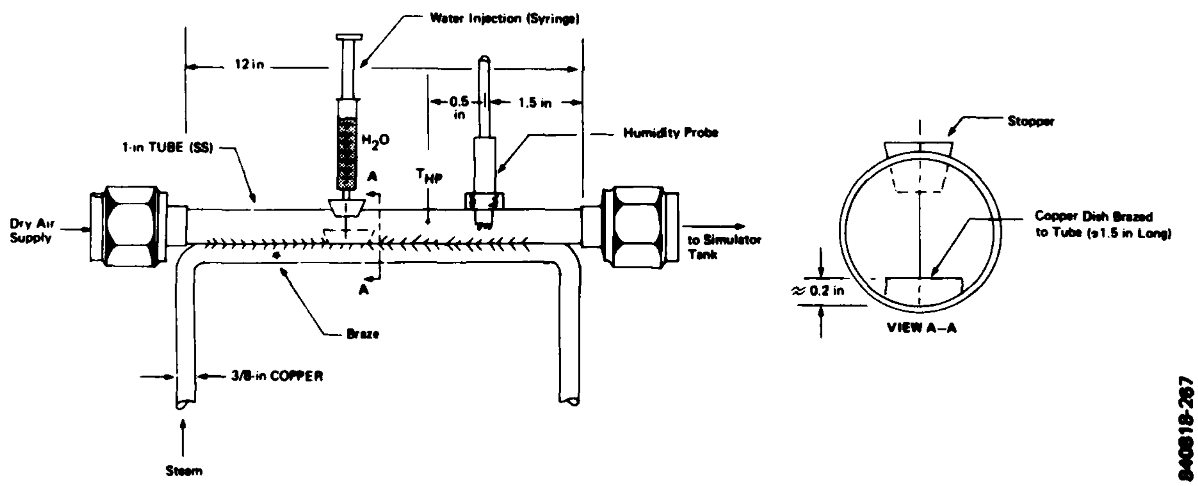


FIGURE 19. WATER EVAPORATOR APPARATUS

At the completion of the simulated descent, the tank was topped off with fresh test AMK fuel and the flight profile repeated. The flight profile test sequence was repeated four times. The water content of the fuel was determined for the fresh test fuel, for the tank fuel after each flight run,

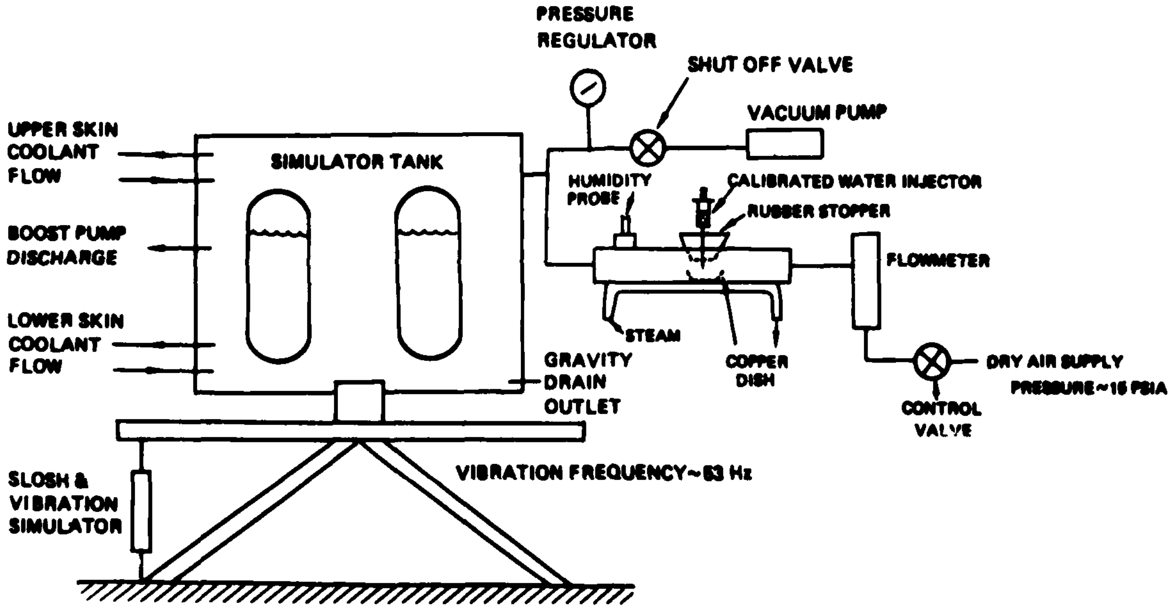


FIGURE 20. WATER VAPOR INGESTION TEST SETUP

after topping off with fresh fuel, and after the final profile run. The procedure used by the Boeing Materials Technology (BMT) laboratory to measure the water content of the fuel samples is described in appendix C.

2.5.3 Water Ingestion Results

Water vapor (2.2 ml) was ingested into the simulator tank using the described procedure. Water vapor was observed to fill the tank ullage within one second after the control valve was opened; the humidity probe registered approximately 100 percent during the process. Some water vapor condensed on the Lexan windows of the test tank during ingestion; however no unusual water vapor/fuel interactions (e.g. strings) were observed during any of the ingestion cycles. At the end of each cycle, the tank had 10 gallons of cold AMK (approximately -37°C) remaining, the surface of which was covered with 1/4-inch thick gel and bubbles which formed as a result of the boost pump operation to drain the tank to the required level. Observations of the nature of the water-AMK reactions on the free surface were made difficult because of this surface gel. At the end of the water vapor test cycle the tank contained approximately 10 gallons of fuel at -36°C plus gel. The tank was then refueled (topped off) with fresh AMK at 16°C, bringing the post-mixing fuel temperature to -4°C; at this temperature all the gel had dissolved back into the fuel.

A review of the motion pictures (64 frames per second) taken during the tests and humidity probe readings indicated that all the boiler water entered the tank in the vapor phase. After the first ingestion cycle the boiler was removed and found to be completely dry, confirming this observation.

After the second water ingestion cycle the fuel became cloudy, presumably because of the increased water content, and remained cloudy even when the fuel was warmed to ambient temperature.

While the orifice cup and filter ratio tests performed on all base AMK samples prior to the ingestion tests appeared normal, filter ratio tests performed on fuel samples taken after topping off the tank showed a tendency toward plugging of the filter ratio test apparatus after the second cycle. Three special solids content tests (D381) were performed on the fuel samples in an effort to gain insight into the cause of the filter plugging with the following results:

FUEL		SOLID CONTENT
Sample 1	Initial batch (base) AMK	0.286% wt
Sample 2	Post-test, Cycle 1	0.280% wt
Sample 3	Post-test, Cycle 2	0.284% wt

These results indicate that the solids content remained essentially constant during the water ingestion test cycles and were not the cause of plugging of the filter ratio screen. Subsequently, water analysis tests showed that the replenishment AMK used for these tests contained relatively high (190 ppm) amounts of water as received, and was not typical. It is now believed that the plugging problem arose because of mixing cold AMK and warm replenishment AMK with a high water content.

Because the high water content in the base AMK fuel tended to mask the effects of the relatively small amount of ingested water, all four cycles were repeated with in-line blended fuel (see Section 3.1). An FAA test engineer was present during these repeat tests and the filter ratio test results were normal. Visual observations (including motion pictures) of the ingestion process were the same as those reported above, i.e., there were no apparent adverse fuel/water reactions. Water content measurements performed on the AMK samples withdrawn from the tank are given in table 6. The results showed that the amount of water which might accumulate in the fuel during repeated descents through water saturated clouds had no deleterious effects on the AMK in the tank.

TABLE 6. RESULTS OF WATER VAPOR INGESTION TEST SAMPLE ANALYSIS (IN-LINE BLENDED AMK)*

No.	Sample Description	Water Content (ppm)	Viscosity (cS)
1	Fresh AMK	66	3.51
2	Post-water vapor ingestion 1st cycle	108	3.97
3	Post-refueling 1st cycle	97	3.93
4	Post-vapor ingestion 2nd cycle	127	4.19
5	Post-refueling 2nd cycle	128	4.13
6	Post-vapor ingestion 3rd cycle	112	3.91
7	Post-refueling 3rd cycle	118	3.97
8	Post-water vapor ingestion 4th cycle	132	4.04
9	Post-refueling 4th cycle	191	4.14

* Water content of the Jet A used to prepare the AMK was measured in ppm, (appendix C)

3. COMPONENT PERFORMANCE TESTS WITH LOW TEMPERATURE FUEL

The purpose of the component tests was to compare AMK and Jet A performance in modern transport airplane fuel system components when operating at low fuel temperatures, and to determine any physical and/or flammability property changes of the antimisting test fuel. The tests included capacitance gauging, suction feed, boost pump, and jet pump operation. All tests were run at bulk mean fuel temperatures (the temperature monitored by the flight crew) of ambient, -20°C, and -40°C. All tests were run first with Jet A to establish baseline performance. The AMK test fuel used in the tests was freshly blended prior to each run using the FAA provided in-line blender (figure 21).

In each component test with AMK, freshly blended AMK was transferred from an intermediate weigh tank by gravity to the simulator tank. After the tank was full, a two-gallon fuel sample taken from the simulator was characterized with the orifice cup and filter ratio tests prior to beginning the test run. The test proceeded only if the results of the filter ratio and orifice cup tests were within the limits prescribed by the FAA for fresh AMK (a filter ratio of 45 or higher and orifice cup flow rates within the range 1.8 to 3.0 ml/30 sec). If the results of the characterization tests were not satisfactory, either the FCTA or solid content tests were required before the main test could be performed. If all the characterization tests indicated unsatisfactory quality of AMK, that fuel was discarded and fresh AMK prepared. At the end of each test run, any AMK fuel remaining in the simulator tank was drained so that the next run could start with a fresh supply of in-line blended AMK. Characterization data for various test runs are presented in table 7, and experience in operating the blending unit is reported in appendix D.

3.1 Capacitance Gauging

The capacitance gauging systems used in commercial airplanes require a number of tank units distributed judiciously throughout the tank to measure fuel quantities at any airplane attitude and fuel level. The tank unit is typically made of two concentric aluminum cylinders each of which acts as the plate of a cylindrical capacitor when a voltage is applied. Since the dielectric constant of jet fuel is about twice that of air, the capacitance of the tank unit is directly related to the fuel level in the gauge. A compensator unit may be installed at the bottom of the tank where it is always fully immersed in fuel to correct for the temperature effects on fuel dielectric constant. In an actual airplane installation, one height volume calibration curve suffices because density and dielectric constant variations are accounted for by the compensator units, or by a densitometer in newer systems.

Capacitance gaging tests performed on a typical airplane unit were combined with the low temperature flight simulation tests, runs 1 to 7. These tests were performed with ambient, -20°C and -40°C Jet A and AMK test fuels.

3.1.1 Calibration Procedure

Initial calibration of the capacitance gauging unit was performed by filling the simulator tank incrementally with known quantities of Jet A fuel at ambient temperature and then incrementally emptying the tank to check repeatability. The height of fuel measured with a graduated scale was

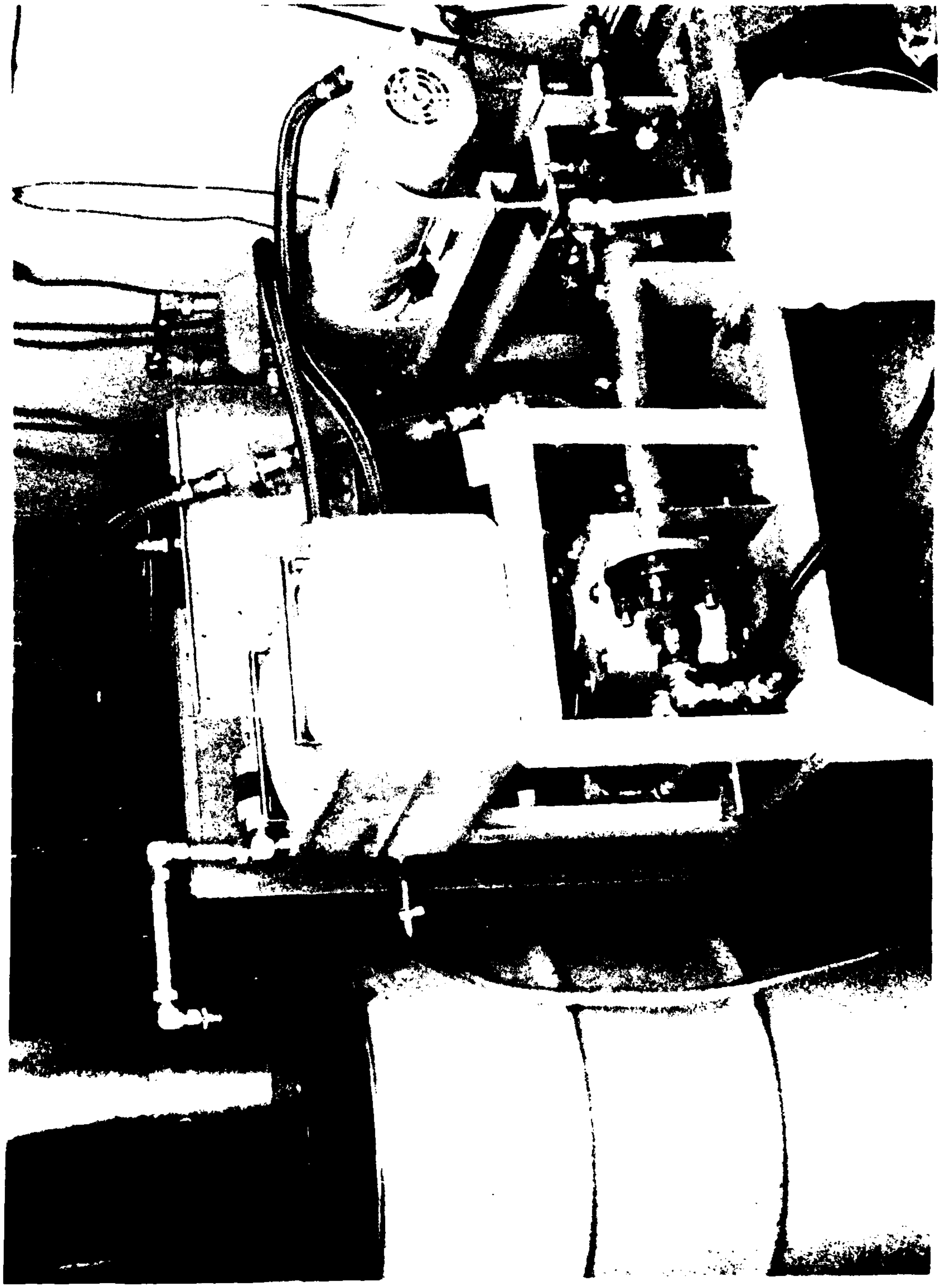


FIGURE 21. IN-LINE BLENDER

TABLE 7. SUMMARY OF IN-LINE BLENDED AMK FUEL CHARACTERIZATION

Sample Number	Date of Blending	Batch Quantity (gallons)	Stabilization Time Before F.R./ O.C. Test (minutes)	Filter Ratio	Orifice Cup (ml/30 sec)	Solids Content (% wt)
1	10-6-83	60	40	46	2.8,2.8	0.196
2	10-7-83	60	50	42	2.4,2.5	-
3	10-7-83	60	60	54	2.2,2.2	-
4	10-14-83	60	40	61	2.6,2.6	0.232
5	10-17-83	60	40	70	2.4,2.5	-
6	10-18-83	60	50	67	2.4,2.5	-
7	10-19-83	60	40	62	2.3,2.4	-
8	10-20-83	60	35	58	2.6,2.7	-
9	11-17-83	60	40	65	2.5,2.6	-
10	11-17-83	60	40	57	2.2,2.3	0.25
11	11-18-82	60	50	62	2.2,2.3	
12	11-21-83	60	45	92	1.7,1.8	0.284
12a	11-21-83	-	-	-	-	1.56
13	12-16-83	60	50	85	2.1,2.2	0.36*
14	1-9-84	120	1 day	83	2.2,2.3	0.30
15	1-13-84	15	3 days	62	1.8,1.8	0.32
16	1-17-84	120	40	73	2.0,2.1	
17	1-19-84	240	40	68	1.9,1.9	
18	1-25-84	60	120	73	1.9,2.0	0.30
19	1-25-84	40	35	42	1.9,2.0	
20	1-26-84	40	90	67	2.0,2.1	
21	1-27-84	40	60	54	1.8,1.9	
22	1-28-84	40	1.5 days	60	1.9,2.0	
23	1-31-84	2200	720	65	1.7,1.8	0.295

*Unmixed slurry from weigh tank

Notes:

Samples 1 to 9 were mixed with a 5 GPM Jet A pump on the blender
Samples 10 to 12 were mixed with an air driven Jet A pump at 2.5 to 8 gpm
Samples 13 to 20 were mixed with an air driven Jet A pump at 8 gpm

recorded for each fueling increment. From these data a height volume baseline calibration curve for the tank could be established. Care was taken in the ambient temperature tests to obtain calibration curves for the Jet A and the antimisting fuels at the same temperature. For the low temperature Jet A tests at -20°C and -40°C, the calibration was conducted by filling the tank with fuel, cooling the fuel to the appropriate bulk temperature, and draining the fuel in approximately the same volume increments as for the ambient temperature calibration.

Antimisting fuel was tested using the same calibration procedures at each of the above temperatures and the gauge performance was compared with that obtained with Jet A fuel.

3.1.2 Results

The capacitance gauge functioned normally, i.e. similar to Jet A, with AMK fuel at all temperatures tested. AMK data are presented in table 8.

Graphs of these data show that the capacitance varied linearly with fuel height within a narrow band of uncertainty. Tests performed with ambient, -20°C, and -40°C AMK indicate that a capacitance gauge designed for Jet A fuel may be used to accurately determine the AMK fuel level in an airplane fuel tank over the -40°C to ambient temperature range without need for recalibration. These data (as well as Jet A data) are plotted in figure 22; a least squares fit of all the data is shown as the solid line, where the RMS deviations are ±3.3 percent.

3.2 Suction Feed

During airplane performance flight tests, engine suction feed capability must be demonstrated at the airplane service ceiling to prove that the fuel feed system can supply the engine in the event of a boost pump failure. Under these emergency conditions, adequate fuel flow must be maintained through the airplane fuel system under the air pressure and gravity head to the engine-driven pump, and the engine driven pump must be able to operate at the reduced inlet pressure condition. Fuel flowability is impeded by the increase in viscosity at low fuel temperatures and combined with low ullage pressure at high altitudes can create a condition of inadequate engine flow in the fuel feed line. The engine feed line length and geometry for a typical (B767) wide-body transport airplane (figure 23) were used to model the airplane feed line resistance from the fuel tank to an actual Pratt and Whitney JT-9D engine feed pump driven by a 35 HP Varidrive (figure 24). Comparison was made with Jet A performance to evaluate the performance of the AMK fuel. Each fuel was tested at three different temperatures (ambient, -20°C and -40°C) and three simulated altitudes (30,000, 35,000 and 40,000 ft).

3.2.1 JT-9D Engine Pump

The JT-9D engine pump is a two-stage pump (centrifugal first stage, gear pump second stage) which is designed to develop approximately 1100 psid, at 72 gpm and 6000 rpm. The centrifugal stage employs an inducer ahead of the main impeller. The inducer, by virtue of its design, can operate satisfactorily with a considerable amount of vapor phase present on the suction surface of the blades. During the suction feed tests the pump speed was reduced from the

TABLE 8. GAUGING DATA FOR TEST FUEL AT DIFFERENT TEMPERATURES

Fuel	Temperature (^{o}C)	Record No.	Fuel Height (in)	Capacitance (pF)
AMK	16.1	1	0	19.2
		2	61.62	24.3
		3	62.62	25.3
		4	63.25	26.1
		5	64.25	27.0
		6	65.37	28.5
		7	66.0	29.2
		8	67.0	30.1
		9	67.94	31.4
		10	69.25	32.5
		11	70.56	34.0
		12	71.37	34.9
		13	72.62	36.7
AMK	-19.5	1	72.0	36.9
		2	70.38	34.4
		3	68.37	32.1
		4	66.50	30.4
		5	64.62	28.0
		6	62.8	25.9
		7	60.74	23.8
AMK	-36.9	1	71.38	36.2
		2	69.25	33.1
		3	67.00	30.2
		4	64.75	28.1
		5	61.75	24.4
JetA	22.2	1	59.38	21.9
		2	61.00	23.7
		3	61.88	24.3
		4	63.88	26.5
		5	65.88	28.8
		6	67.88	30.8
		7	69.81	32.9
		8	71.69	35.3
		12	72.69	36.4
		13	72.19	35.9
		14	71.75	35.5
		15	71.19	34.7
		16	70.75	34.0
		17	70.25	33.4

TABLE 8. (CONTINUED) GAUGING DATA FOR TEST FUEL AT DIFFERENT TEMPERATURES

Fuel	Temperature (^{o}C)	Record No.	Fuel Height (in)	Capacitance (pF)
Jet A	22.2	19	69.50	32.6
		20	68.94	32.2
		21	68.69	31.9
		22	68.25	31.4
		23	66.31	29.5
		24	64.50	27.3
		25	62.69	25.2
		26	60.56	23.2
Jet A	1.7	1	60.00	21.9
		2	61.31	24.1
		3	61.94	24.9
		4	63.88	26.4
		5	65.69	28.6
		6	67.56	30.8
		7	69.50	32.7
		8	71.19	34.8
Jet A	-20	11	67.25	30.8
		12	64.94	27.9
		13	63.13	26.0
		14	61.13	24.0
		15	59.38	21.8
Jet A	16.7	1	N.A.	21.3
		2	60.25	22.8
		3	61.81	24.7
		4	64.00	27.6
		5	65.81	29.2
		6	67.81	30.7
		7	69.75	33.4
		8	71.56	35.0
Jet A	-33.9	12	72.13	36.6
		13	71.44	35.7
		14	70.63	34.7
		15	69.88	33.3
		16	69.00	32.4
		17	68.00	31.8
		18	66.25	30.2
		19	64.31	27.5
		20	62.25	24.9
		21	60.31	23.2

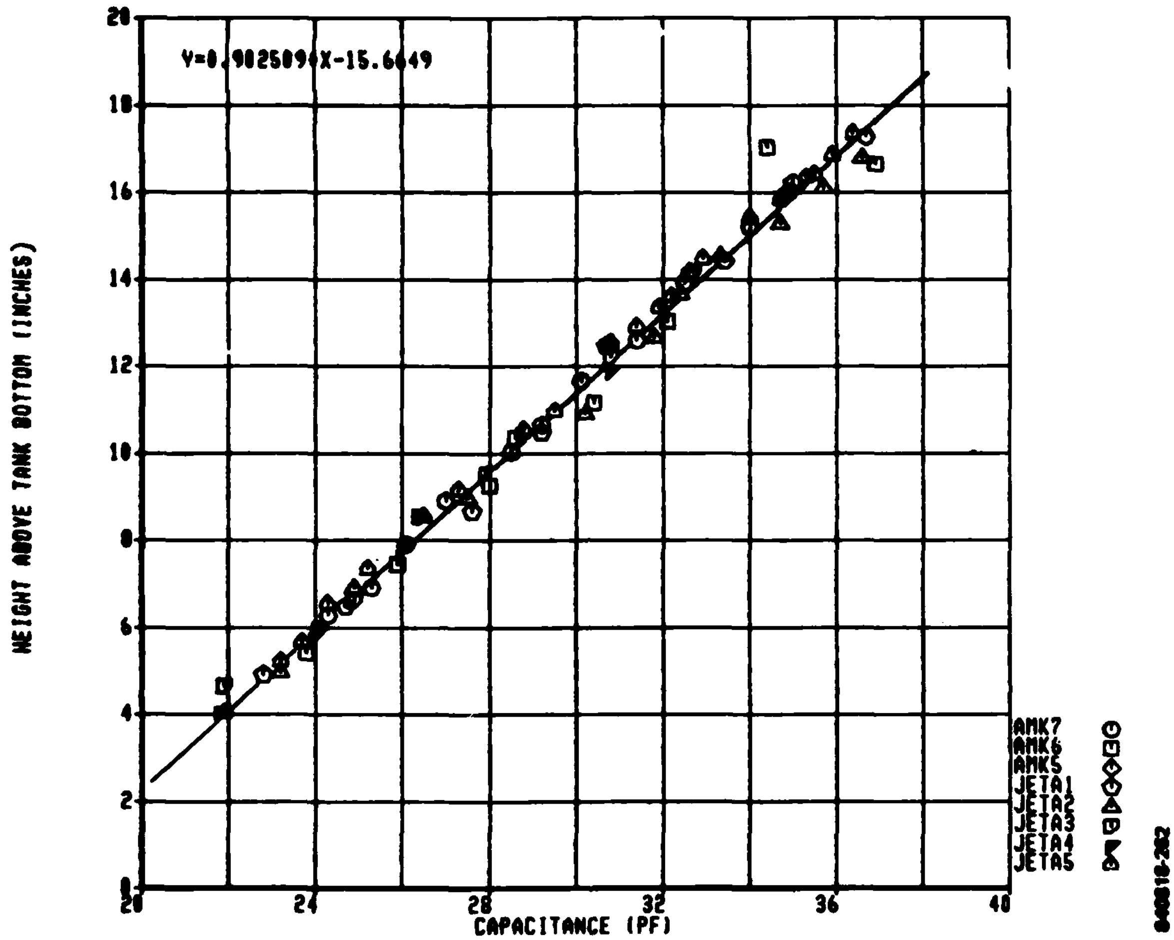


FIGURE 22. CAPACITANCE GAUGE CALIBRATION DATA

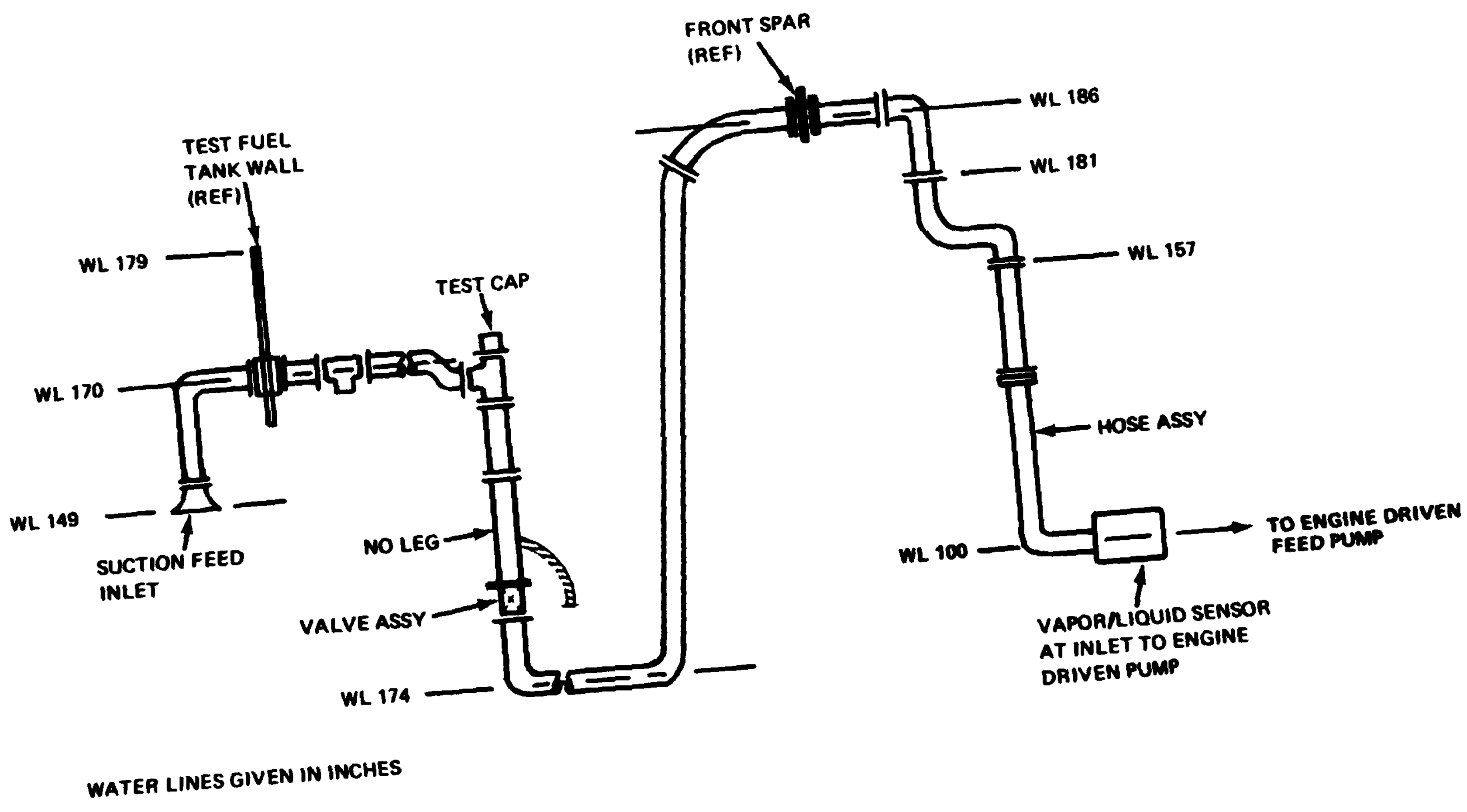


FIGURE 23. B 767 AIRPLANE FUEL FEED SYSTEM - LEFT WING

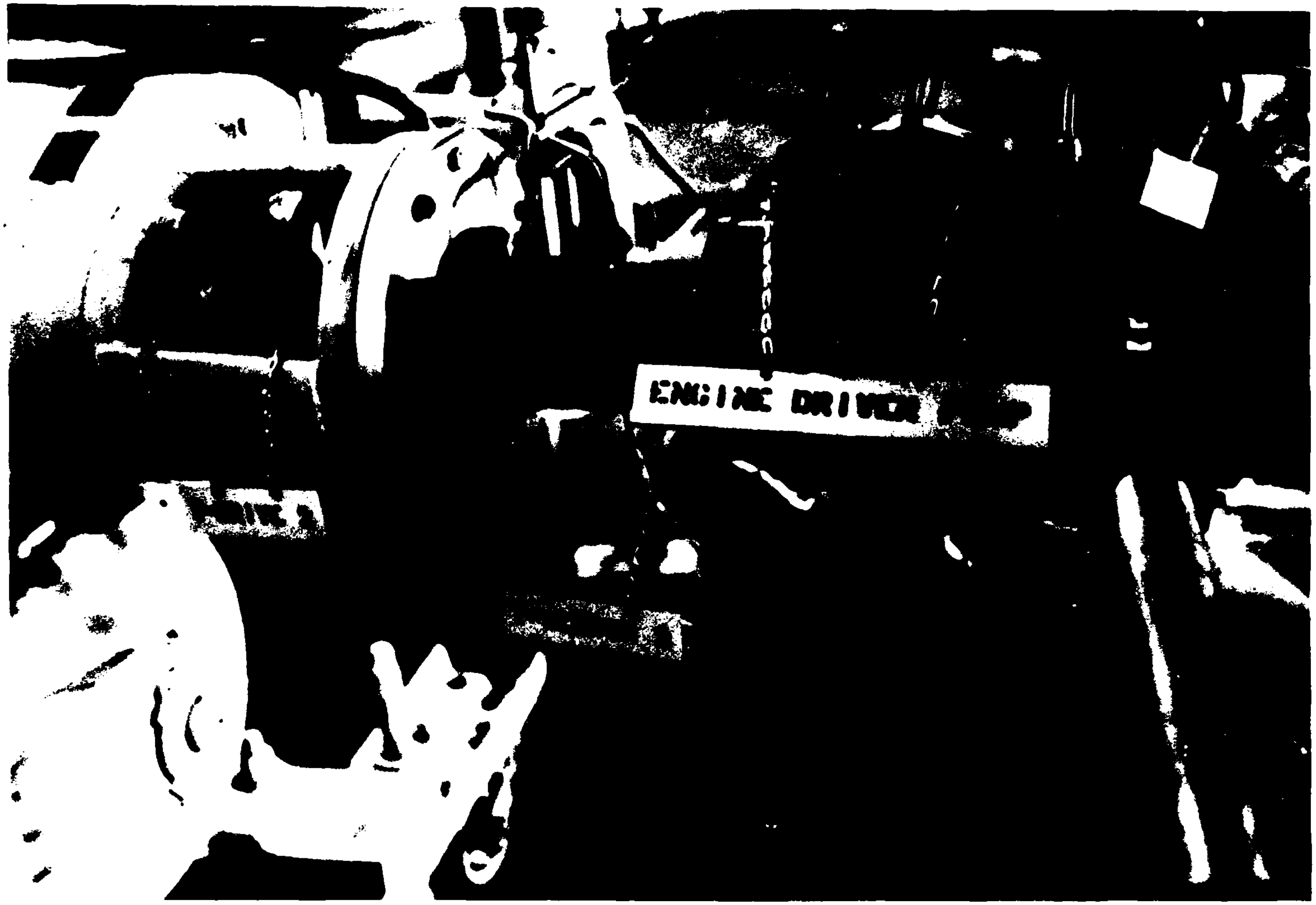


FIGURE 24. ENGINE DRIVEN PUMP TEST APPARATUS

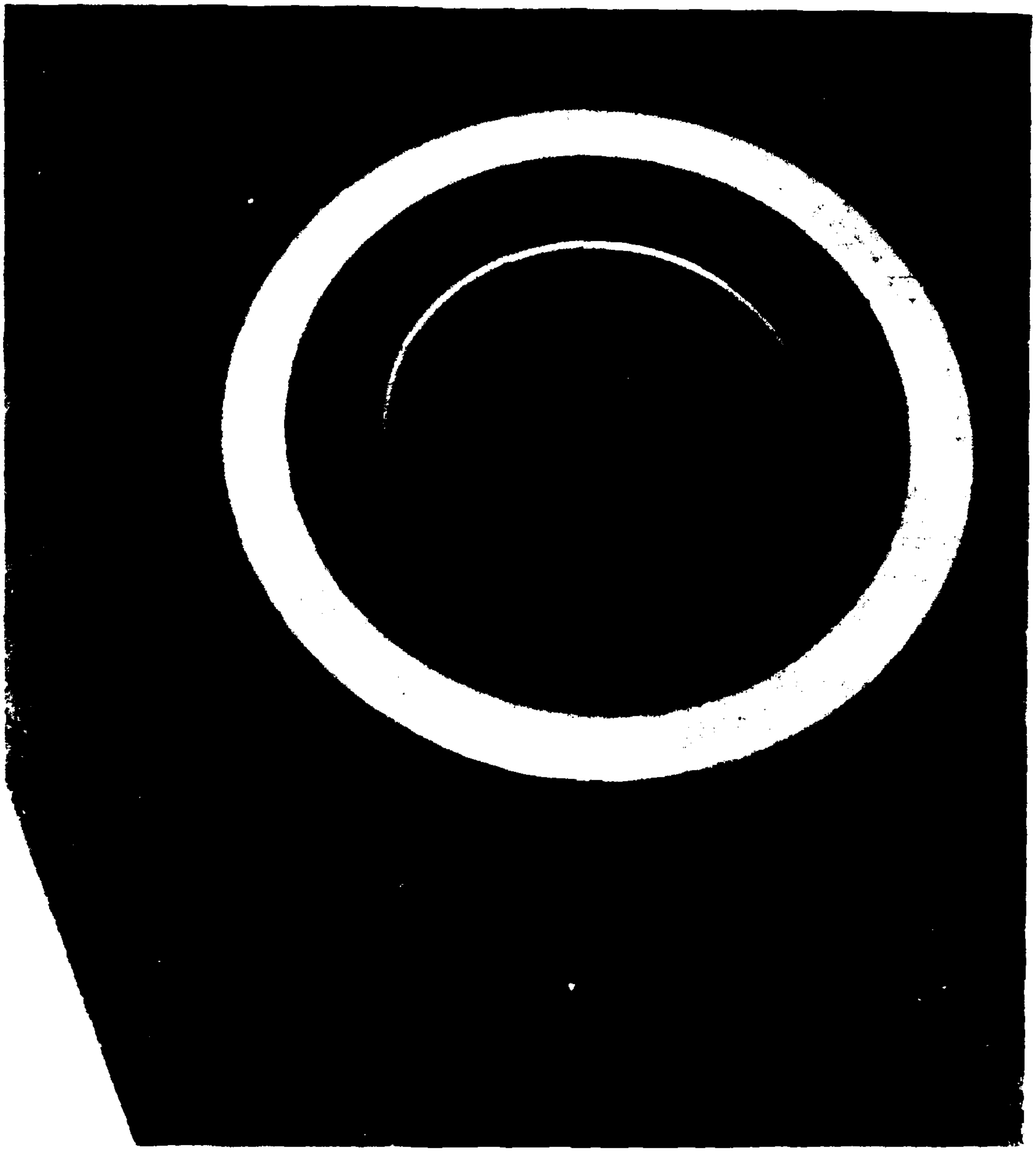


FIGURE 25. JT-9D ENGINE DRIVEN PUMP INTERSTAGE FILTER

design speed to model the cruise flow condition approximately 15-20 gpm. A 40-micron paper cartridge filter (effective area 100 in^2), shown in figure 25 is incorporated between the centrifugal and gear stages; this filter has a bypass valve which normally opens at a pressure of 8 to 9 psid. This interstage filter provides protection against particulate and from ice crystals at fuel temperatures below freezing. Periodically a fuel deicing heater is activated which clears ice particles from the filter.

3.2.2 Suction Feed Test Set-Up

The simulated B767 suction feed line (figure 26) models the length, the gross elevation changes, and inside line diameters of the airplane suction feed plumbing; the line was insulated to reduce heat transfer effects while pumping cold test fuel. A snorkel inlet to the suction feed line was located inside the simulator tank, to model the boost pump inlet. A transparent straight section of pipe located immediately upstream of the engine driven feed pump facilitated inspection for possible two-phase flow into the pump.

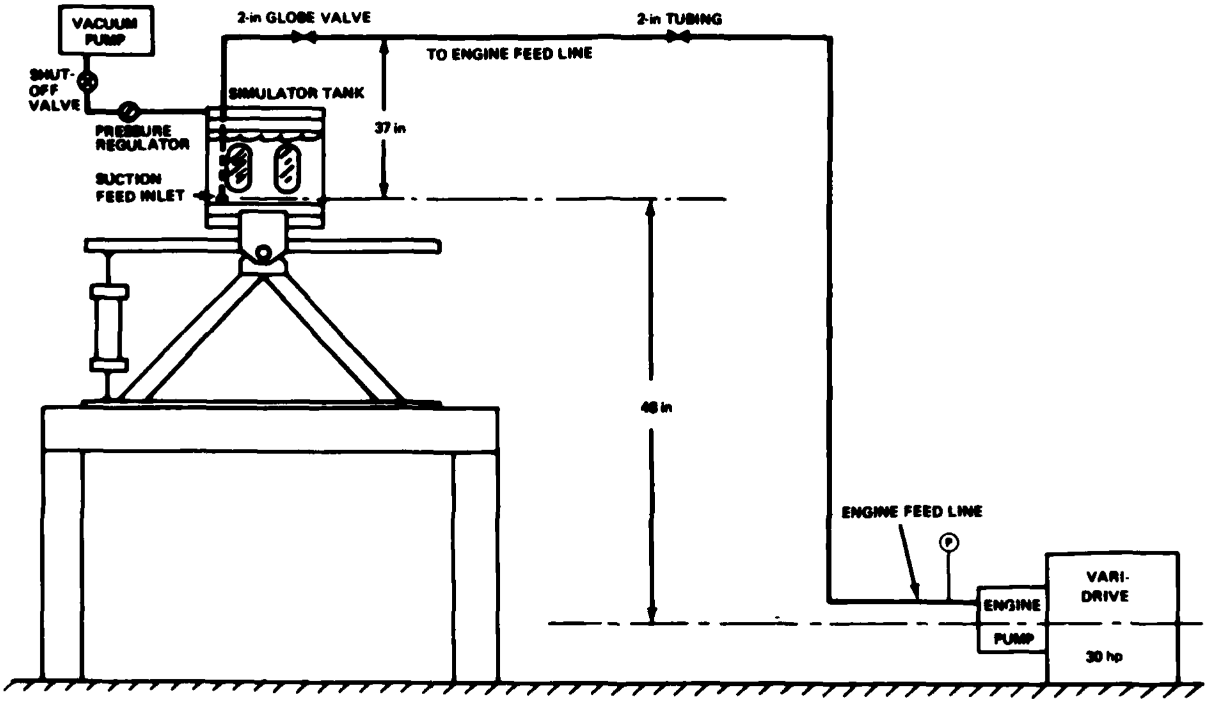


FIGURE 26. TEST CONFIGURATION FOR SUCTION FEED PERFORMANCE

3.2.3 Test Procedure (Runs 17 to 34)

The simulator tank was filled with test fuel (either Jet A or in-line blended AMK) and cooled to the desired temperature, which was then held constant during the test. The tank ullage pressure was next reduced to the desired pressure altitude using a vacuum pump. During suction feed with Jet A at ambient temperature, the fuel could be returned to the simulator tank for continuous operation. However, with cold Jet A or AMK the fuel supply was limited to approximately 50 gallons, which translated into roughly 2 minutes of steady flow operation at the cruise flow rate.

It was found during preliminary operational tests that the suction feed line required priming before the engine driven pump could operate satisfactorily. This step was accomplished by filling the suction feed line with the boost pump just prior to turning on the engine feed pump. After the desired flow and discharge pressure of the engine pump had been established, the boost pump was switched off, simulating the "loss of boost pump" condition. The success or failure of the test was determined by the measured flow rate and discharge pressure of the JT-9D engine driven pump. Adjustments to the engine driven pump were made with ambient temperature Jet A, using re-circulated fuel to extend the test duration. The pump bypass and flow control valves were adjusted manually until a pressure of approximately 180 psig was achieved at a flow rate of 20 gpm. The fuel level in the simulator tank was closely monitored during the test and the time of suction feed failure was recorded. When the tank was empty or when the suction feed failed, the engine pump was stopped and tank cooling was terminated. Some repeat runs were performed with both Jet A and AMK to verify the repeatability of the tests; in all cases, the original results were confirmed. After the final suction feed test, the interstage filter was removed and inspected for possible gel formations.

3.2.4 RESULTS

The important variable in these tests was the pump flow rate, which will fall off sharply if the inlet total pressure to the pump falls below a critical value. The suction feed results are summarized in table 9. Success (S) implies

TABLE 9. SUCTION FEED PERFORMANCE TEST RESULTS

Fuel	Temperature ^{o}C	Simulated Altitude (ft) 30,000	35,000	40,000
Jet A	Ambient	S	S	S
	-20	S	S	S
	-40	M	F	F
AMK	Ambient	M	M	F
	-20	S	F	F
	-40	S	M	M

S = Success, 20-30 gpm, 100-180 psi discharge pressure
M = Marginal, 5-10 gpm, < 100 psi discharge pressure
F = Failure, < 1 gpm, < 10 psi discharge pressure

a flow rate adequate to maintain cruise power; marginal (M) implies a flow rate at which the engine would lose power, but continue operating; and failure (F) a flow rate at which the engine would probably flameout. The results indicate that suction feed performance with -40^{o}C Jet A would be poor, because of viscosity effects; for Jet A, viscosity increases roughly 300 percent when the fuel temperature is reduced from 0^{o}C to -40^{o}C. With AMK, suction feed performance was poor with ambient and -20^{o}C fuel but improved at -40^{o}C where it was better than Jet A. The FM-9™ antimisting additive apparently enhances the flowability of AMK at the very low temperatures.

Polymeric type additives similar to FM-9™ are commonly used in oil pipelines to improve flowability at low temperatures. Plugging of the interstage filter was not observed during the AMK runs.

3.3 Boost Pump Performance

Several concerns underlay the test of antimisting fuel in boost pumps. The electrical power requirements were expected to be higher because of the higher apparent viscosity of the fuel. The long narrow passages used for cooling the boost pump motor were identified as potential problem areas. If these passages were restricted significantly or blocked when pumping antimisting fuel, the boost pump case temperature might increase to unacceptable values. Orifice flow tests performed with AMK have shown that small white globules would collect in an orifice, causing reduced flow rates (reference 3). These formations were attributed to the interaction of FM-9 and water. Therefore, there was also concern about the possibility of similar reactions between the antimisting additive and water leading to gum-like deposits in the boost pump. Finally, local degradation of the AMK was anticipated from the shearing action in the boost pump vapor removal line.

3.3.1 Test Pump

Boost pump performance tests were conducted on a B747 main boost pump, (Hydro-Aire Model 60-755). A cut-away view and an exploded view of the boost pump are given in figures 27 and 28. The pump is designed to be self priming and for this purpose includes a vapor removal flow system which returns approximately 5 gpm to the fuel tank. This pump was installed in the 50-gallon simulator tank used in the AMK environmental tests (figure 2). At maximum or cruise engine power, the boost pump flow rates are such that the time available to record steady state performance data is of the order of from one to three minutes. During this relatively short period of time the boost pump case temperature increase was not significant and therefore was not measured. (A better indication of the heating effects was provided from the 2-hour boost pump endurance tests reported in section 4.)

The initial orientation and location of the vapor discharge flow (figure 2) was not representative of actual airplane installation, i.e., in the airplane, vapor is discharged at a point far removed from the suction inlet. The vapor removal line was subsequently re-routed to the opposite side of the tank prior to the boost pump tests.

3.3.2 Test Procedure

Tests were performed with Jet A and fresh in-line blended AMK at bulk fuel temperatures of ambient, -20°C, and -40°C with the pump deadheaded and at flow rates simulating cruise and maximum power. The following variables were measured during the tests:

- pump discharge flow rate
- pump discharge pressure
- input power
- vapor removal flow rate
- tank temperatures

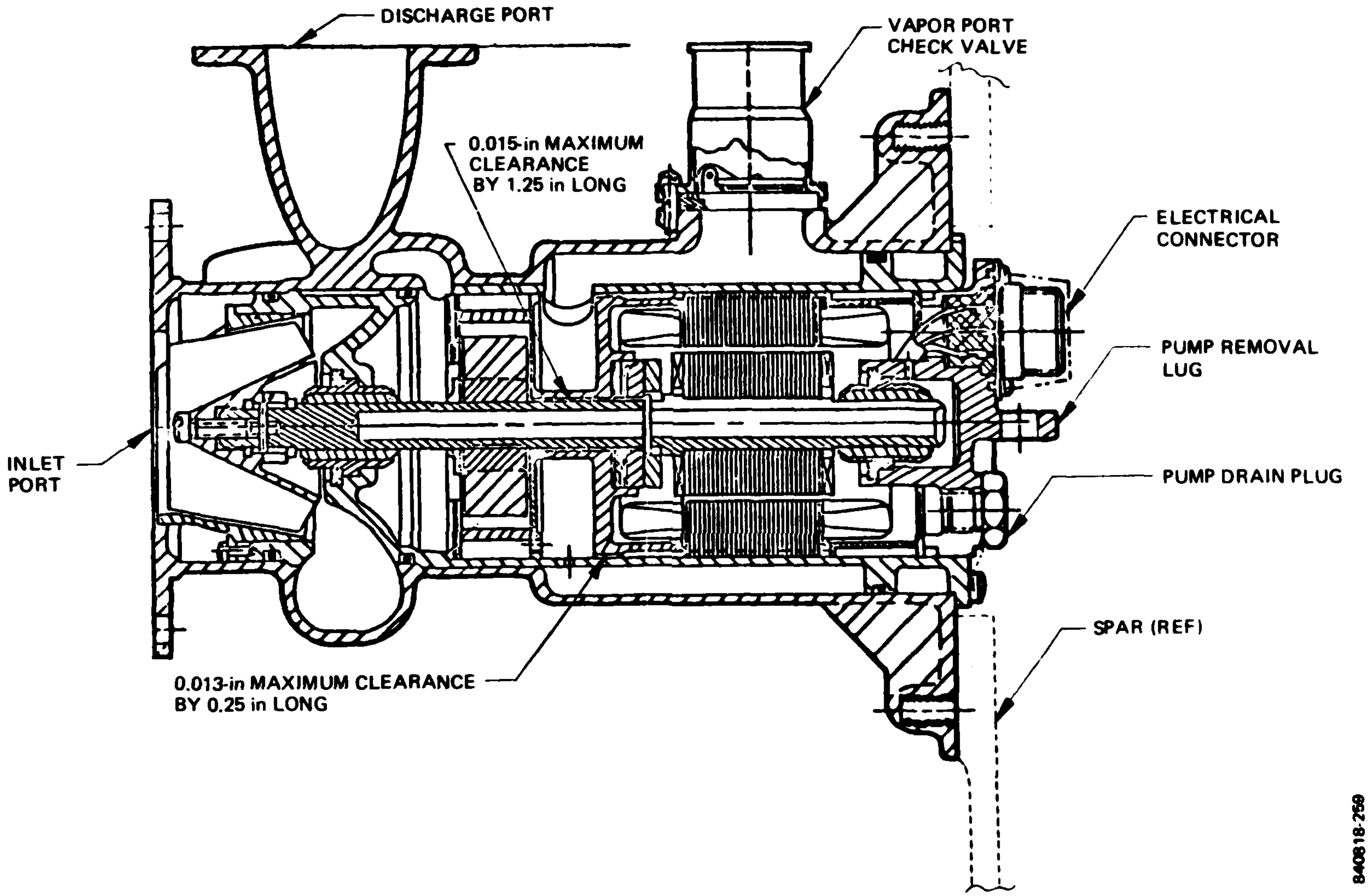


FIGURE 27. CUTAWAY VIEW OF BOOST PUMP

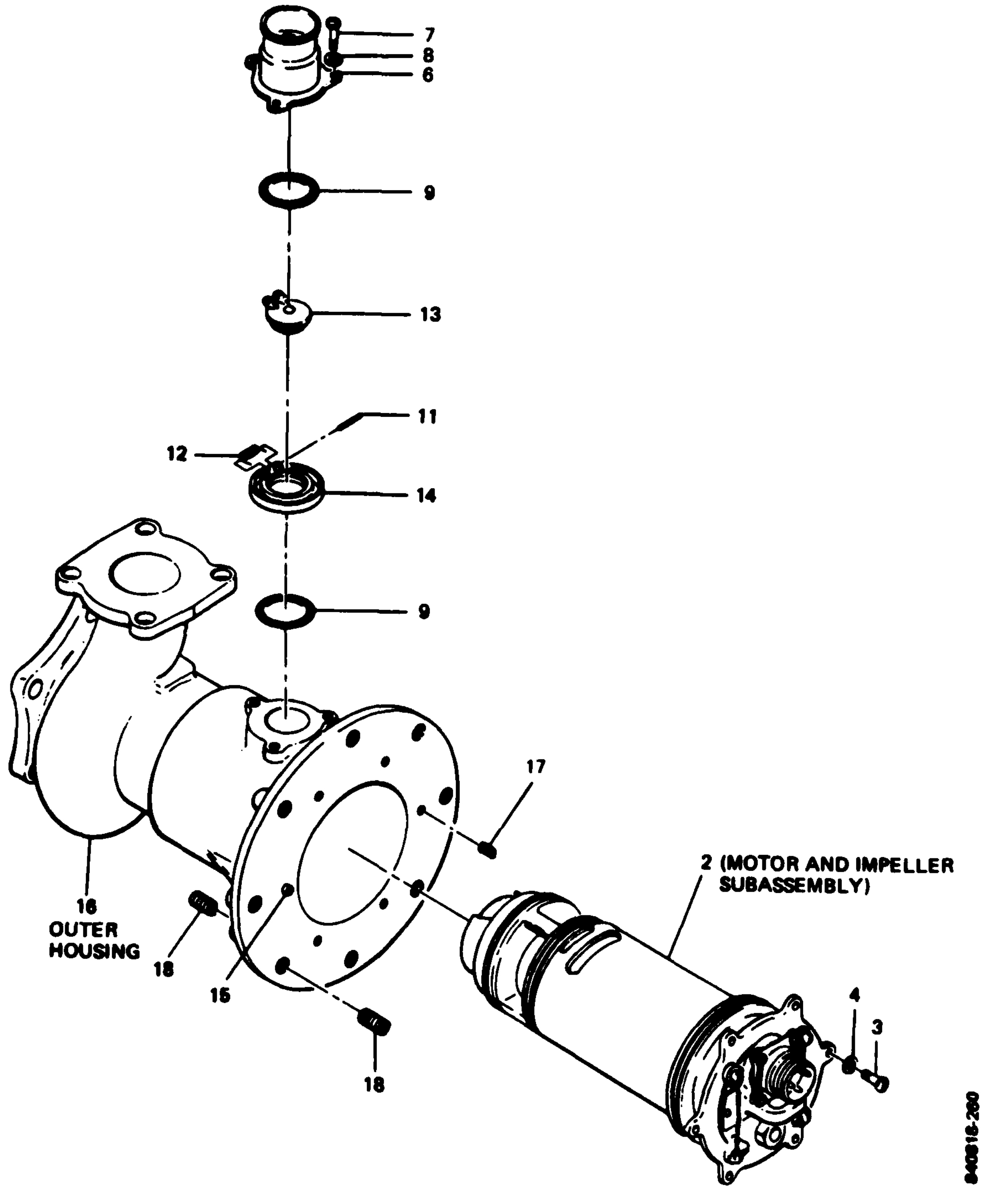


FIGURE 28. EXPLODED VIEW OF BOOST PUMP

Flow rates were measured using the mass versus time method. For this method, the pump discharge was routed to a weigh tank suspended from a load cell, which provided a complete flow rate history. The flow rate through the vapor removal pump could be measured in a similar manner using a valve located in the vapor removal line; this allowed the vapor removal flow to be either recirculated back to the simulator tank or routed to a weigh tank. AMK fuel samples were taken from the vapor removal flow and from the simulator tank during the test. The extent of degradation produced by the vapor removal flow was of interest, since the boost pumps normally run continuously during a flight and it would be undesirable to degrade significant quantities of fuel. During the test, the boost pump operation was monitored visually through the tank windows.

Prior to the boost pump tests, the boost pump was disassembled and inspected to determine if any anomalies had developed in previous tests. Jet A fuel was tested first, followed by tests with the antimisting fuel. Upon completion of the test series, the boost pump was again disassembled and inspected.

3.3.3 Results

During all tests with AMK the boost pump operated with no observable difficulties. In boost pump operation with -20°C and -40°C AMK, gel formations were formed during the low temperature tests and were observed to float on the free surface of the fuel. As the gel was not observed until the boost pump was switched on and since no gel was observed at any time in the boost pump discharge, the surmise is that the gel formed during the shear interaction between the vapor/liquid discharge jet and the surrounding AMK. These formations disappeared from the residual tank fuel following the tests as the fuel warmed up.

Jet A and AMK steady flow performance data for this pump are reported in table 10, while boost pump pressure versus flow rate data are plotted in figure 29. A comparison of the steady flow power requirement for pumping Jet A and AMK is reported in table 11; these data were collected during the environmental test series.

The performance data show the following trends:

- the power requirement increases as temperature decreases with Jet A, with the reverse trend for AMK.
- power requirements for pumping AMK were always higher than for Jet A.
- pump efficiency tended to decrease with temperature with Jet A. With AMK this trend was reversed, with improving pump efficiency at lower temperature. At -40°C the pump efficiency was higher for AMK than for Jet A.
- vapor removal flow rates were approximately the same for both fuels at the same test conditions.

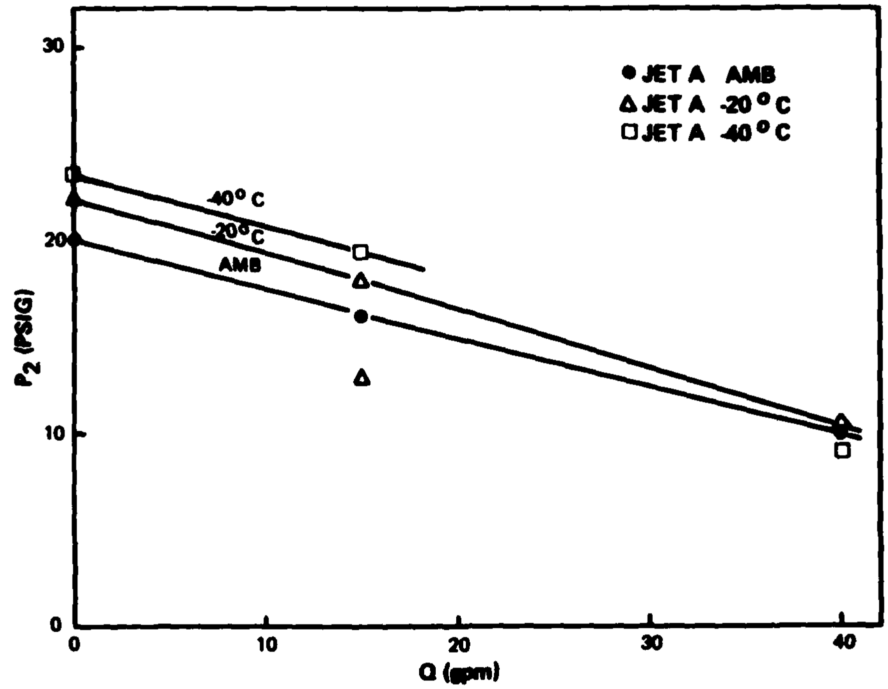
After the completion of the boost pump performance tests, the pump was disassembled and inspected. It was not possible to determine whether gel formations existed within the pump during operation (especially at low temperatures), since inspection could not be accomplished until the pump had been disassembled. By this time the pump components had warmed to ambient temperature. In any event, no unusual gel formations or wear of the parts were detected during this inspection.

TABLE 10. STEADY FLOW BOOST PUMP PERFORMANCE

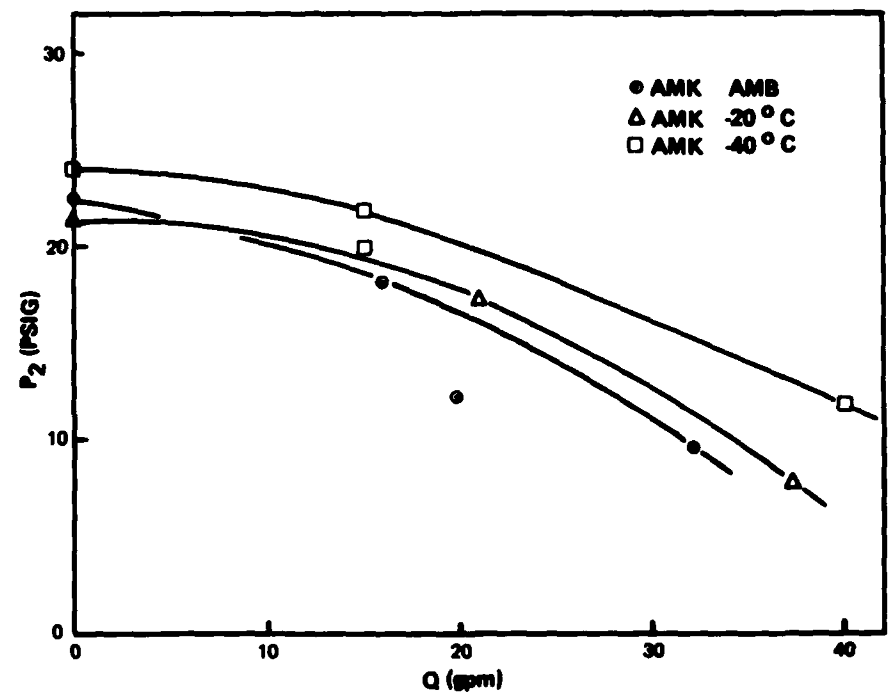
Run No.	Description	T (°C)	B.P. Discharge Pressure (psig)	B.P. Flow Rate (gpm)	Input Power (hp)	Develop Fluid Power (hp)	Vapor Removal Flow (lb/min)	Overall Effciency (%)
Jet A								
35	Max Power	AMB	10.0	40.0	2.09	0.233	6.1	11.1
36	Cruise Power	AMB	17.3	15.0	2.06	0.140	12.8	7.3
37	Dead Head	AMB	20.0	0.0	2.09	-	21.0	-
39	Max Power	-20	11.1	40.0	2.21	0.259	7.8	11.7
40	Cruise Power	-20	19.0	12.9	2.16	0.143	12.9	6.6
41	Dead Head	-20	22.0	0.0	2.29	-	19.3	-
43	Max power	-40	9.0	40.0	2.35	0.210	6.3	8.9
44	Cruise Power	-40	19.5	15.0	2.24	0.171	13.0	7.6
45	Dead Head	-40	23.5	-	2.33	-	16.3	-
AMK								
48	Max Power	-40	12.0	40.0	2.52	0.28	6.0	11.1
49	Cruise Power	-40	20.2	15.0	2.50	0.18	10.2	7.2
50	Dead Head	-40	24.0	0.0	2.51	-	16.9	-
52	Dead Head	-20	21.0	0.0	2.46	-	19.2	-
53	Cruise Power	-20	22.1	18.0	2.55	0.23	11.9	9.0
54	Max Power	-20	8.0	37.6	2.71	-	21.1	-
56	Dead Head	AMB	22.4	-	2.57	-	21.1	-
58	Cruise Power	AMB	12.6	20	2.92	0.15	12.4	5.1
59	Max Power	AMB	9.9	32	2.67	0.19	4.7	7.1

TABLE 11. COMPARISON OF JET A AND AMK BOOST PUMP POWER REQUIREMENTS

Run No.	Fuel	Temperature (°C)	Power (KW)	Power Difference $\left(\frac{\text{AMK-Jet A}}{\text{Jet A}}\right) \times 100$ %
4	Jet A	Ambient	1.50	18.0
9	AMK	Ambient	1.77	
3	Jet A	-20	1.61	15.3
8	AMK	-20	1.85	
2	Jet A	-30	1.66	
7	AMK	-30	1.74	4.8



a. JET A



b. AMK

FIGURE 29. BOOST PUMP DISCHARGE PRESSURE VS. FLOW RATE PERFORMANCE

The results of fuel sample characterization tests performed during the boost pump tests are summarized in table 12. Flammability test results are not reported in table 12, because after they were performed, a piece of packing material was found lodged in the FCTA fuel supply line invalidating the data.

3.4 Jet Pump Performance

Jet pumps are used in transport airplanes for fuel transfer and for water scavenge. In Boeing airplanes, jet pumps are only used to scavenge water from low points in the main fuel tanks and deliver it to the main boost pump suction inlet where small quantities of water can be pumped through the feed system to the engines without incident. In the B747, for instance, eight Allen Aircraft 68E108 jet pumps (figure 30) are used in the water scavenge system. Data reported by Ching and Peacock (reference 7) show that jet pump performance with AMK is lower than with Jet A. In pumping water and AMK mixtures with jet pumps, there was a concern that AMK/water reactions might cause partial or total blockage of the jet pumps, especially when the fuel was cold. In the B747 water scavenge system, the jet pump motive flow is provided from a tee fitting installed in the pressure switch tap in each main boost

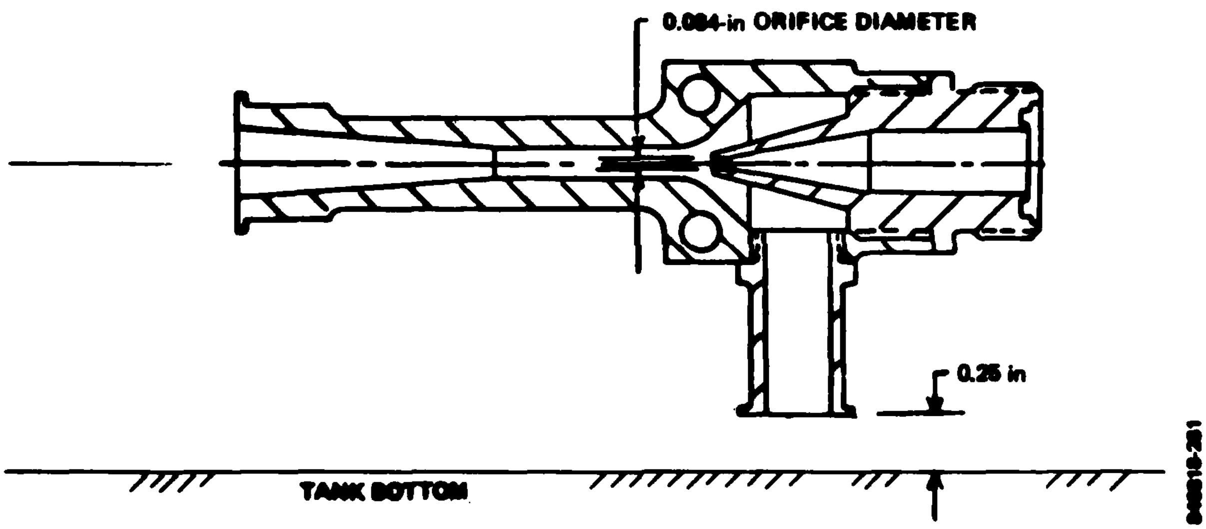


FIGURE 30. DETAILS OF WATER SCAVENGE JET PUMP

pump discharge elbow. An orifice is installed in the motive flow branch to reduce the boost pump pressure to about 7 psig. The ejector motive flow (approximately 0.4 gpm) has a negligible effect on boost pump discharge pressure and flow rate and does not affect fuel feed system performance. Therefore, a blocked water scavenge pump normally would not have any deleterious effect on engine performance. The main concern was that the effects caused by not removing water from the AMK on a timely basis might lead to undesirable accumulation of water over a period of time. There is, of course, the possibility that high concentrations of water in airplane tanks might not be a problem with AMK because of AMK's affinity to water, eliminating the need for the continuous water scavenge system.

TABLE 12. AMK CHARACTERIZATION RESULTS, BOOST PUMP PERFORMANCE TESTS

Run No.	Sample Conditions	Orifice Cup	Filter Ratio
--	Fresh AMK, -40°C Tests 2.5 Days After Blend	2.1, 2.2	84.6
47	-40°C Max Power Boost Pump Discharge	2.3, 2.2	57.0
47*	Vapor Removal	2.6, 2.7	55.1
48	-40°C Cause Power Boost Pump Discharge	2.3, 2.2	62.1
48*	Vapor Removal	2.3, 2.4	58.1
49	-40°C Dead Head Boost Pump Discharge	1.8, 1.7	92.0
49*	Vapor Removal	2.0, 1.9	82.7
--	Fresh AMK, -20°C Tests 45 Min After Blend	2.3, 2.2	83.0
51	-20°C Max Power Boost Pump Discharge		
51*	Vapor Removal	2.2, 2.3	64.0
52	-20°C Cruise Power Boost Pump Discharge		
52*	Vapor Removal	2.3, 2.3	71.0
53	-20°C Dead Head Boost Pump Discharge		
53*	Vapor Removal	2.4, 2.4	52.0
--	Fresh AMK Ambient 50 Min After Blend	1.9, 1.9	68.0
55	Ambient Max Power Boost Pump Discharge		
55*	Vapor Removal	1.9, 1.8	74.0
56	Ambient Cruise Power Boost Pump Discharge		
56*	Vapor Removal	2.3, 2.3	60.0
57	Ambient Dead Head Boost Pump Discharge		
57*	Vapor Removal	2.1, 2.2	58.0

*Same run conditions except sample taken from vapor removal discharge line.

In airplanes where the jet pump is used for fuel transfer, pump plugging would be a much more serious concern, possibly leading to failure of the fuel feed system.

3.4.1 Design Performance

Jet pump performance characteristics can conveniently be presented by plotting the pressure ratio N as a function of the entrainment ratio, ϕ where,

$N = (P_d - P_i)/(P_m - P_d)$
$\phi = Q_i/Q_m$
P_d = discharge pressure
P_i = suction pressure
P_m = motive flow pressure
Q_i = induced flow
Q_m = motive flow

Jet pump efficiency is defined as

$$\eta = 100\ (\phi)(N).$$

The design Jet A performance curve for the B747 ejector (68E108) is given in figure 31. The dashed line is the predicted performance curve for Jet A at -40°C. The motive flow for the ejector can be calculated from the formula

$$Q_m = 54 \sqrt{P_m - P_i}\ , \qquad (5)$$

where pressure and flow rate are in units of psi and lb/hr, respectively.

The nominal design operating performance conditions for the 68E108 pump are as follows:

- o motive flow = 0.35 gpm
- o motive flow pressure = 7 psig
- o suction flow = 0.5 to 0.6 gpm
- o efficiency ≈ 22 percent

3.4.2 Test Procedure

The jet pump performance test set-up is shown schematically in figure 32. The tests were begun with a full tank at atmospheric pressure (suction inlet pressure approximately 15.3 psia) and with the boost pump flow rate adjusted to a nominal 15 gpm. As fuel was pumped from the tank by the boost pump and the jet pump, ambient temperature air was drawn into the tank through the vent system. When the upper end of the jet pump rake became uncovered, warm air was drawn into the scavenge rake (simulating the situation in a nearly empty tank) and the jet pump inlet performance was expected to deteriorate.

Jet A tests (runs 38, 42, 46) were performed first, at temperatures of ambient, -20°C, and -40°C. The jet pump discharge flow was routed to a weigh tank and measured using the mass versus time technique. Pressure transducers were installed in the motive flow and discharge lines as shown in figure 32. Data were recorded by the same system used in the environmental test series. Subsequently the tests were repeated with AMK at the same three nominal temperatures.

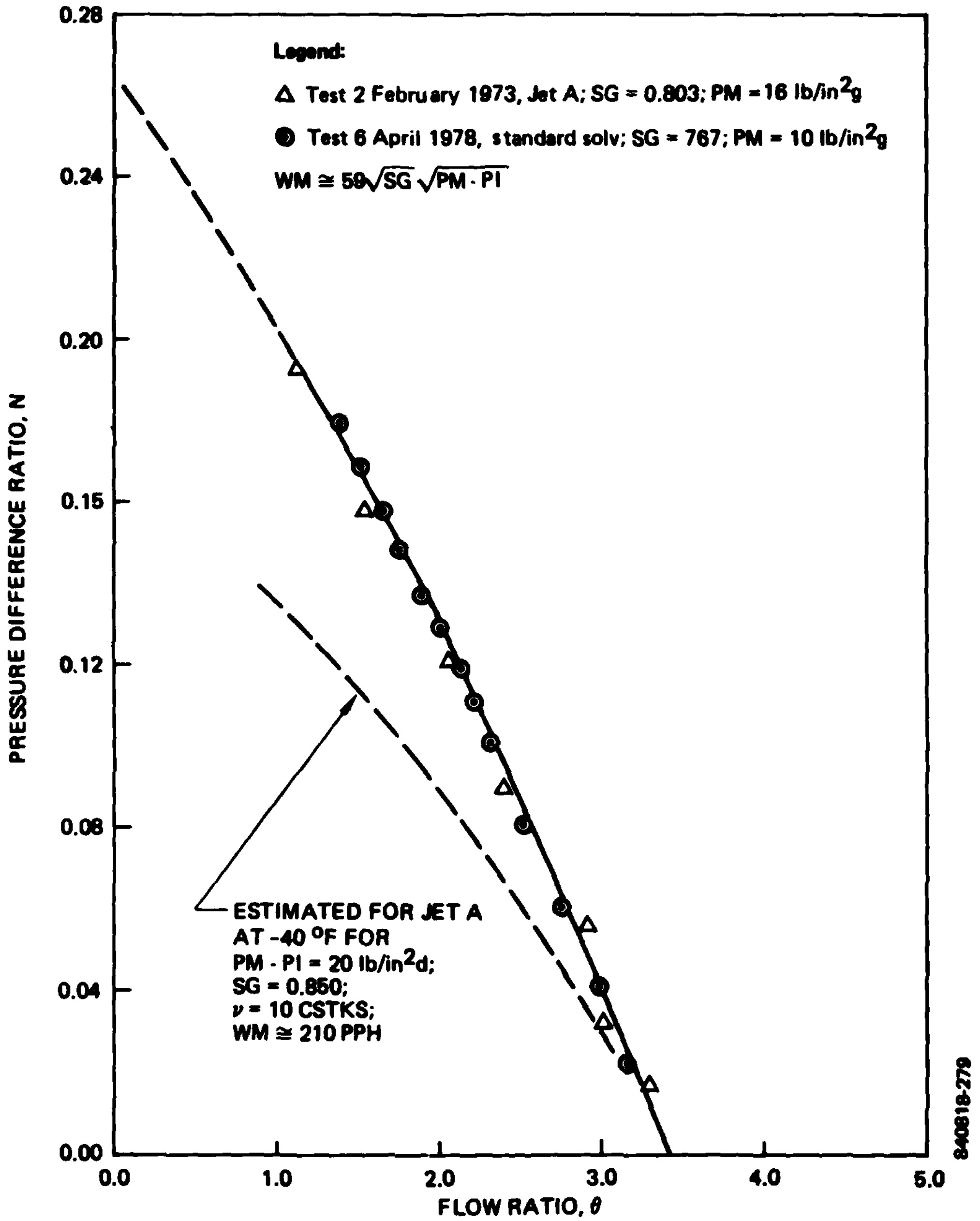
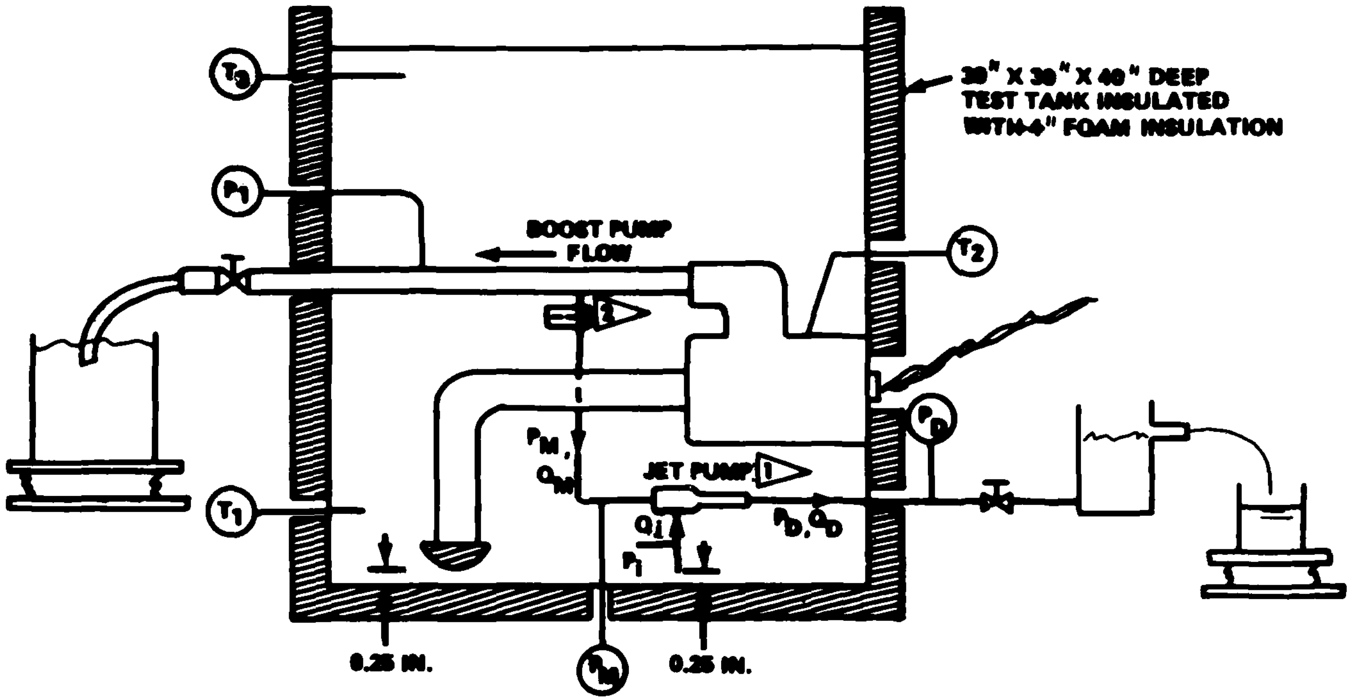


FIGURE 31. DESIGN PERFORMANCE DATA, WATER SCAVENGE JET PUMP



NOTES

1. [illegible]E108 JET PUMP - ALLEN AIRCRAFT PRODUCTS B747 WATER SCAVENGE PUMP
2. .0[illegible] IN. DIA. ORIFICE MOTIVE FLOW BRANCH
3. COOLING COIL INSIDE TEST TANK

FIGURE 32. JET PUMP TEST SETUP

The orifice (0.0595 inch diameter) installed in the jet pump motive flow line was also used to measure the motive flow rate. Orifice calibrations were performed at ambient temperature with Jet A and AMK with the induced flow line capped. The calculated orifice Reynolds number for these runs was 1.1×10^4. The following calibration equation was used to compute the motive flow, Q_m,

$$Q_m = C \sqrt{\Delta p} \quad (6)$$

where, Q_m = motive flow (gpm)
$\Delta p = p_1 - p_m$
p_1 = boost pump discharge pressure
p_m = jet pump motive pressure
C = 0.08633 Jet A
C = 0.08192 AMK

The discharge coefficient, C, is a function of Reynolds number and is nearly constant for $Re > 10^4$. At low temperatures the Reynolds number will decrease because of the higher viscosity, therefore the values of C will be slightly higher. At -40°C, values of C will be approximately 4 percent higher than those reported above. This correction was not made in the computed values of Q_m.

3.4.3 Results

The jet pump performance and fuel characterization results are reported in tables 13 and 14, respectively. The results showed the following:

- o Jet A results at ambient agreed with the design values.
- o AMK performance was substantially lower than that for Jet A at ambient and -20°C AMK.
- o At -40°C the performance with AMK was approximately the same as that for Jet A at the same temperature.
- o The jet pump produced very little apparent degrading of AMK at any of the test temperatures.
- o The velocity head $(\frac{\rho V^2}{2})$ is quite small in all cases.

When the fuel level dropped below the upper leg of the jet pump inlet, a slight drop in flow rate was observed when pumping Jet A (all three temperatures). However, under similiar conditions with the AMK, the reduction in flow was very pronounced. It was not possible to measure these changes in flow rate due to the short test time. At both -20°C and -40°C small amounts of gel (strands) were observed at the jet pump discharge with AMK fuel.

4. BOOST PUMP ENDURANCE TESTS

The component test times in the 50-gallon cold fuel simulator were of relatively short duration because of the small tank capacity with respect to the size of the boost pump. A smaller boost pump could have been adapted to the simulator tank for longer run times, but since this program was devoted to

TABLE 13. JET PUMP PERFORMANCE RESULTS, BOOST PUMP FLOW = 15.0 ± 1.5 GPM.

Run No.	Test Fuel	T (^oC)	P_1 (psig)	P_m (psig)	Q_m (gpm)	Q_1 (gpm)	P_d (psig)	Q_d (gpm)	V_D* (ft/s)	$\frac{\rho V_D^2}{2g_c}$ (psi)	$P_{d,t}$ (psi)	N x_{10^2}	ϕ	%
--	Jet A	13.0	19.4	5.66	0.32	0.00		0.32	1.0	0.0005		--	--	--
--	AMK	16.4	20.4	4.15	0.32	0.00		0.32	1.0	0.005		--	--	--
46	Jet A	13.0	19.3	6.51	0.31	0.61	0.49	0.92	2.8	0.04	0.53	8.86	1.96	17.4
58	AMK	16.4	20.8	5.21	0.32	0.31	0.38	0.63	1.9	0.02	0.40	8.32	0.97	8.1
42	Jet A	-20.9	21.1	7.84	0.32	0.49	0.49	0.81	2.5	0.03	0.52	7.10	1.53	10.9
54	AMK	-20.5	22.1	6.90	0.32	0.00	0.63	0.32	1.0	0.005	0.64	10.2	0	0
38	Jet A	-40.8	22.4	8.42	0.32	0.37	0.55	0.69	2.1	0.02	0.57	7.26	1.16	8.4
50	AMK	-40.9	23.2	8.70	0.31	0.34	0.54	0.65	2.0	0.02	0.56	6.88	1.09	7.5

*Based on 3/8" exit i.d.

TABLE 14. AMK CHARACTERIZATION RESULTS, JET PUMP PERFORMANCE TESTS

Run No.	Test Conditions*	Orifice Cup	Filter Ratio
	AMB AMK RUN BBL #380 Pre-Test	2.8, 2.8	92.0
58	AMB, J.P. Discharge -20^{o}C AMK RUN	2.5, 2.4	70.86
	BBL #374 Pre-Test	2.7, 2.6	72.0
54	-20^{o}C, J.P. Discharge -40^{o}C AMK RUN	2.4, 2.3	65.9
	BBL #354 Pre-Test	2.3, 2.3	100.7
50	-40^{o}C Discharge	2.2, 2.1	88.6

*orifice cup No. A15, No. 222, BS 1733 filter ratio apparatus Ser. No. 3

tests with hardware typical of commercial transport airplanes, the B747 pump was considered more representative. Consequently, questions concerning the long term operation of the boost pump (e.g. heating effects and gel buildup) and effects on the antimisting quality of the boost pump discharge fuel could not adequately be studied in the cold fuel simulator. The boost pump endurance tests were performed to give the needed operating time.

Although the main emphasis of the endurance tests was on the boost pump performance, the test facility afforded an opportunity to observe the operation of a simulated engine feed system degrader and engine filter performance over long periods of time with cold AMK.

4.1 Fuel Feed Simulator

A fuel feed system which simulates portions of a B747 airplane installation (figure 33) was designed and assembled. The system as assembled contained the following features:

- o full-scale geometry
- o B747 production boost pump (override pump)
- o simulation of fuel feed line from boost pump to outboard engine (B747)
- o fuel supply sufficient for 2-hour cruise simulation (15 gpm flow rate)
- o temperature control for maintaining ambient, -20°C and -40°C fuel during test runs
- o an experimental degrader
- o a JT-9D engine driven pump
- o a CF6-50 engine low pressure cartridge filter, a JT-9D engine pump interstage filter and a JT-8D wash flow filter
- o fuel sampling capability at fuel source, upstream and downstream of the degrader, and at the system discharge
- o data acquisition system with "quick look" and magnetic tape generation capability

A 2800 gallon, epoxy lined storage tank (figure 34), was located inside a York low temperature environmental chamber; the boost pump was located in a rectangular housing at the bottom of the tank as shown. The fuel feed line (figure 35) between the boost pump and engine feed pump (representative of a B747 fuel system) was located outside of this chamber. The line was thermally insulated to maintain adiabatic flow from the boost pump to the degrader. With the exception of the torque measurements, the instrumentation and data acquisition system was similar to those used in the environmental and component tests (section 3.1).

4.2 Procedure

Power consumption and fuel delivery tests were performed with a 15-gpm nominal flow rate in the following sequence:

- o Jet A (ambient) steady-state, baseline
- o Jet A (-20°C) steady-state, baseline
- o Jet A (-40°C) steady-state, baseline
- o AMK (ambient), endurance (2 hours)
- o AMK (-20°C), endurance (2 hours)
- o AMK (-40°C), endurance (2 hours)

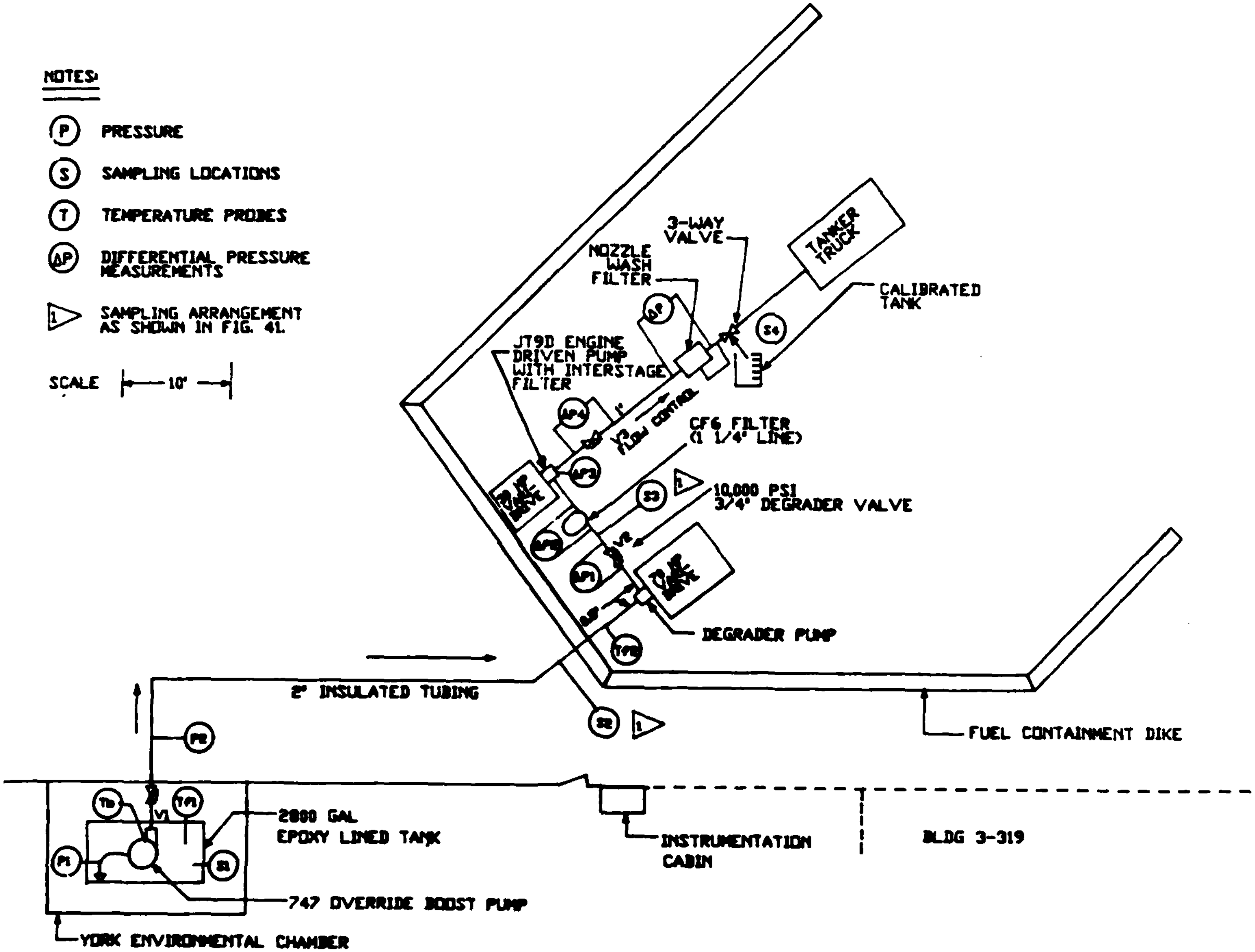


FIGURE 33. BOOST PUMP ENDURANCE TEST SETUP

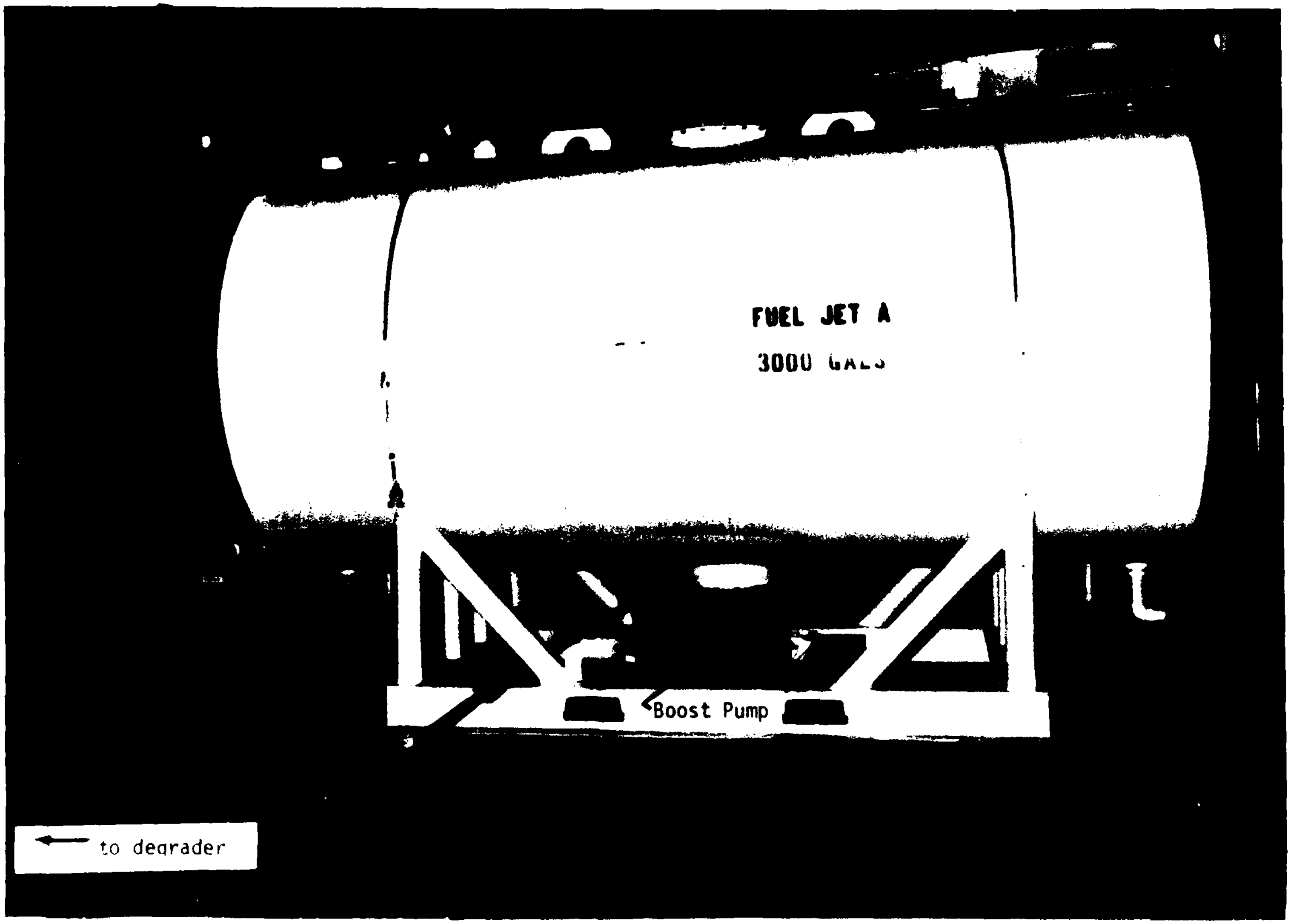


FIGURE 34. BOOST PUMP ENDURANCE TEST SETUP IN ENVIRONMENTAL CHAMBER

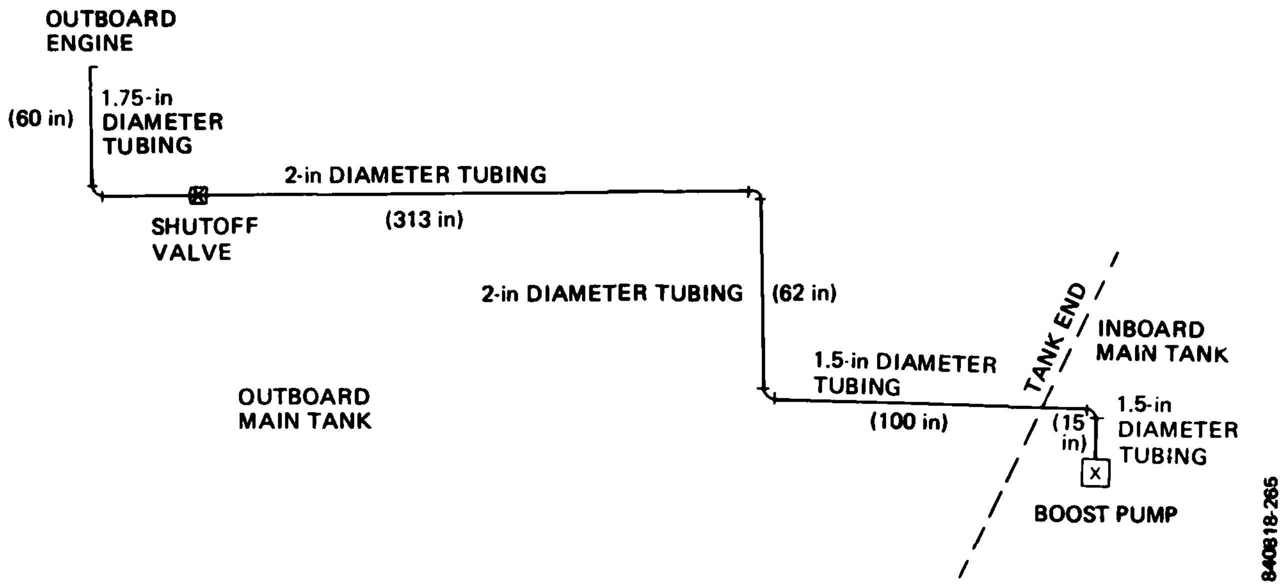
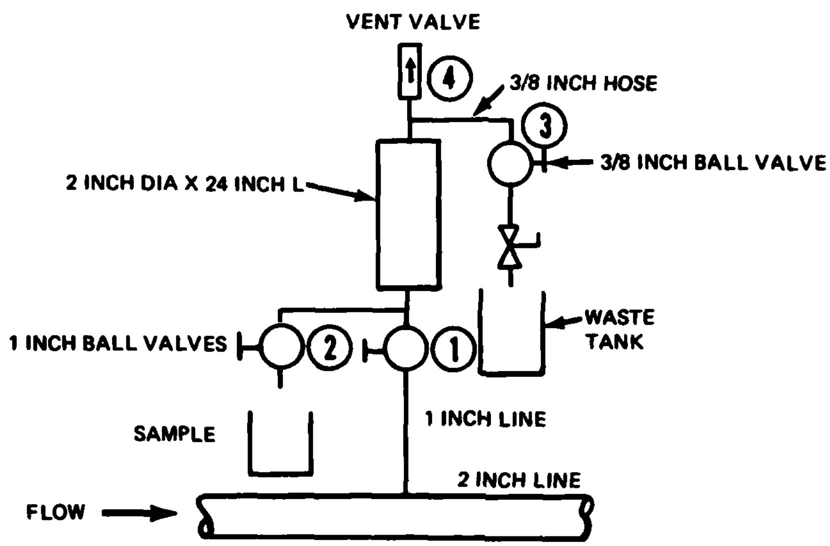


FIGURE 35. SIMULATED 747 BOOST PUMP LINE TO ENGINE

The Jet A tests required about 30 minutes of run time (500 gallons) for each fuel temperature. These tests were performed prior to the AMK runs to obtain steady flow performance data for comparison with AMK and to adjust valve settings (pressures) of the system for the AMK tests.

Freshly prepared in-line blended fuel was used in all the endurance tests (approximately 2000 gallons per run). During the test, samples were drawn from four locations (S1 to S4, figure 33). The design of the sample system and sampling procedures at the pressurized stations S2 and S3 (figure 36) are similar to those used by Coffinberry (reference 6). Samples were taken approximately 30 minutes after startup and near the end of the test (approximately 30 minutes prior to end of test). Orifice cup and filter ratio tests were performed on the day of test (after the sample fuel had warmed to the desired temperatures) and the FCTA tests were generally performed a few days following completion of the test. The results of the characterization tests for the ambient, -20°C, and -40°C endurance tests are summarized in table 15. The filter ratio measurements on samples drawn from the -20°C run showed high values both downstream of the degrader (S3) and at the system discharge (S4). These samples were then heated gradually to 160°F and cooled to ambient temperature to eliminate residual cold fuel (memory) effects which were thought to exist. Although the flammability tests show that this fuel would burn as normal Jet A, the high filter ratio readings indicate the fuel was not completely degraded. In the -40°C tests, this heating/cooling approach was not used prior to characterization.

The waste AMK test fuel was transferred into a tanker truck which was driven to the FAA Technical Center, Atlantic City Airport, N.J., after the completion of the endurance tests. The fuel from each endurance run was loaded into a separate compartment and samples of fuel were drawn from the bottom of each compartment prior to departure. The ambient and -40°C samples appeared clear, however the -20°C sample contained some white precipitate, similar in



When the fuel sample is to be obtained, take the following steps: At the beginning all valves are closed.

1. Open V-3
2. Open V-1
   The test fuel will flow through the sample fuel reservoir, flushing it by discharging into a waste tank through V-3. All throttling will occur at V-3, the fuel within the reservoir remaining unaffected.
3. After about one minute of flushing, close V-1 and open V-2. Collect the discharge from V-3 in a 2 gallon AMK container. Use V-4 to control the flow rate.
4. Close V-2 and open V-1.
   This will allow the sample reservoir to be refilled.
5. Repeat steps 2 through 4 until the 2 gallon sample is obtained.
6. Close valves (1), (2), and (3).

FIGURE 36. AMK ON LINE SAMPLING PROCEDURE (STATIONS S2 AND S3)

TABLE 15. AMK SAMPLE CHARACTERIZATION RESULTS, BOOST PUMP ENDURANCE TESTS

Serial No	Date	Sample Description	FCTA**	Orifice Cup (ml/30 sec)
1	02-01-84	S1, from supply tank after blending 4 batches, Prior to AMB Temp. Test, Run No. 6	Pass (all points)	1.8, 1.7
	02-13-84	S1(1)*Supply Tank	Pass (all points)	1.8, 1.8
		S1(2)	Pass (all points)	1.9, 1.9
		S2(1) Upstream of degrader	Pass (all points)	4.6, 4.5
		S2(2)	Pass (4-points), Fail (2-Points)	4.6, 4.5
		S3(1) Downstream of degrader	Fail (all points)	6.8, 6.9
		S3(2)	Fail (all points)	6.8, 6.7
		S4(1) Collection tank	Fail (all points)	6.0, 5.9
		S4(2)	Fail (all points)	6.2, 6.3
2	02-10-84	S1, from supply tank after blending 4-batches, prior to -20°C Test Run No. 7	Pass all points	2.0, 2.0
	02-16-84	S1(1)+ Supply Tank	Pass all points	2.0, 1.9
		S1(2)+	Pass all points	1.8, 1.8
		S2(1)+ Upstream of degrader	Pass all points	2.2, 2.3
		S2(2)+	Pass all points	2.8, 2.7
		S3(1)+ Downstream of degrader	Pass all points	6.0, 6.1
		S3(2)+ Downstream of degrader	Fail all points	6.8, 6.9
2	02-16-84	S4(1)+ Collection tank, rear comp.	Fail (all points)	5.2, 5.3
		S4(2)	Fail (all points)	6.7, 6.6
		S4(1) Collection tank, center comp.	Fail (all points)	7.2, 7.2
		S4(2)+	Fail (all points)	6.2, 6.3
		S4(3)+	Fail (all points)	7.0, 7.1
3	02-15-84	S1 Fresh AMK (blended 2-14-84 for runs 8&9)	Pass (all points)	1.8, 1.8
		S1(1) Supply tank	Pass (all points)	1.8, 1.8
		S1(2)	Pass (all points)	1.9, 1.9
		S2(1) Upstream of degrader	Pass (all points)	3.8, 3.8
		S2(2)	Pass (all points)	3.6, 3.7
		S3(1) Downstream of degrader	Fail (all points)	6.6, 6.7
		S3(2)	Fail (all points)	6.7, 6.8
		S4(1) Collection tank	Fail (allpoints)	6.4, 6.5
		S4(2)	Fail (all points)	6.7, 6.7
3A	02-24-84	S1(1) Supply tank (-40°C AMK, Run 9)	Pass (all points)	1.7, 1.6
		S1(2)	Pass (all points)	1.8, 1.8
		S2(1) Upstream of degrader		1.8, 1.8
		S2(2)		1.9, 2.0
		S3(1) Downstream of degrader	Fail all points	6.6, 6.7
		S3(2)	Fail (4 points) pass (2 points)	6.9, 6.8
		S4(1) Collection tank	Fail (all points)	5.9, 5.9
		S4(1)+ Collection tank, sample heated to 160°F	Fail (all points)	6.7, 6.8
		S4(2)	Fail (all points)	6.2, 6.3

* Numbers in parentheses refer to time sample was taken during test. (1) = after 1/2 hr (2) = after 1/2 hr.

** Six points tested: air velocity 50 m/s, fuel flow (ml/s) = 12, 14, 16
air velocity 60 m/s, fuel flow (ml/s) = 12, 14, 16

\+ Sample heated to 160°F and cooled to ambient prior to characterization tests

appearance to unmixed slurry. This precipitate, not observed during the endurance test runs, apparently separated and settled to the bottom of the tank during the storage period of approximately 3 weeks. It is possible that gross contamination of the AMK by water from the tanker catch basin was responsible for the precipitation.

4.3 Boost Pump Description

The boost pump used in the endurance tests was a Hydro-Aire Model 60-703 override boost pump (figures 37 and 38) which is installed in the B747 airplane. The pump is of similar design to the B747 main boost pump tested earlier in the program (section 3.3) except that it has a higher capacity and pressure output. The nominal performance characteristics for this pump are reported in table 16 and figure 39. Post-test teardown inspections of the pump were performed after each endurance test.

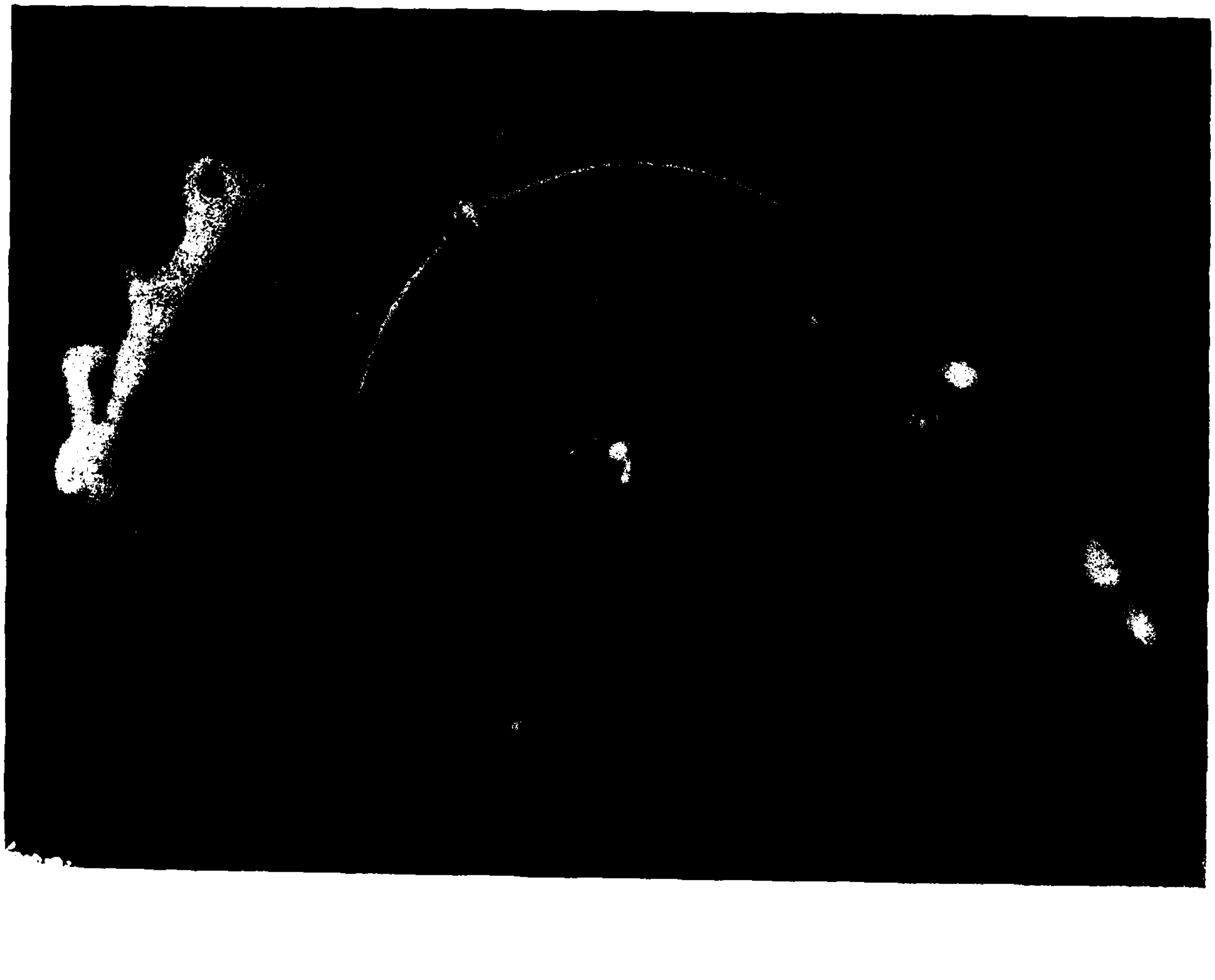


FIGURE 37. BOOST PUMP INLET FOLLOWING -40° AMK ENDURANCE TEST

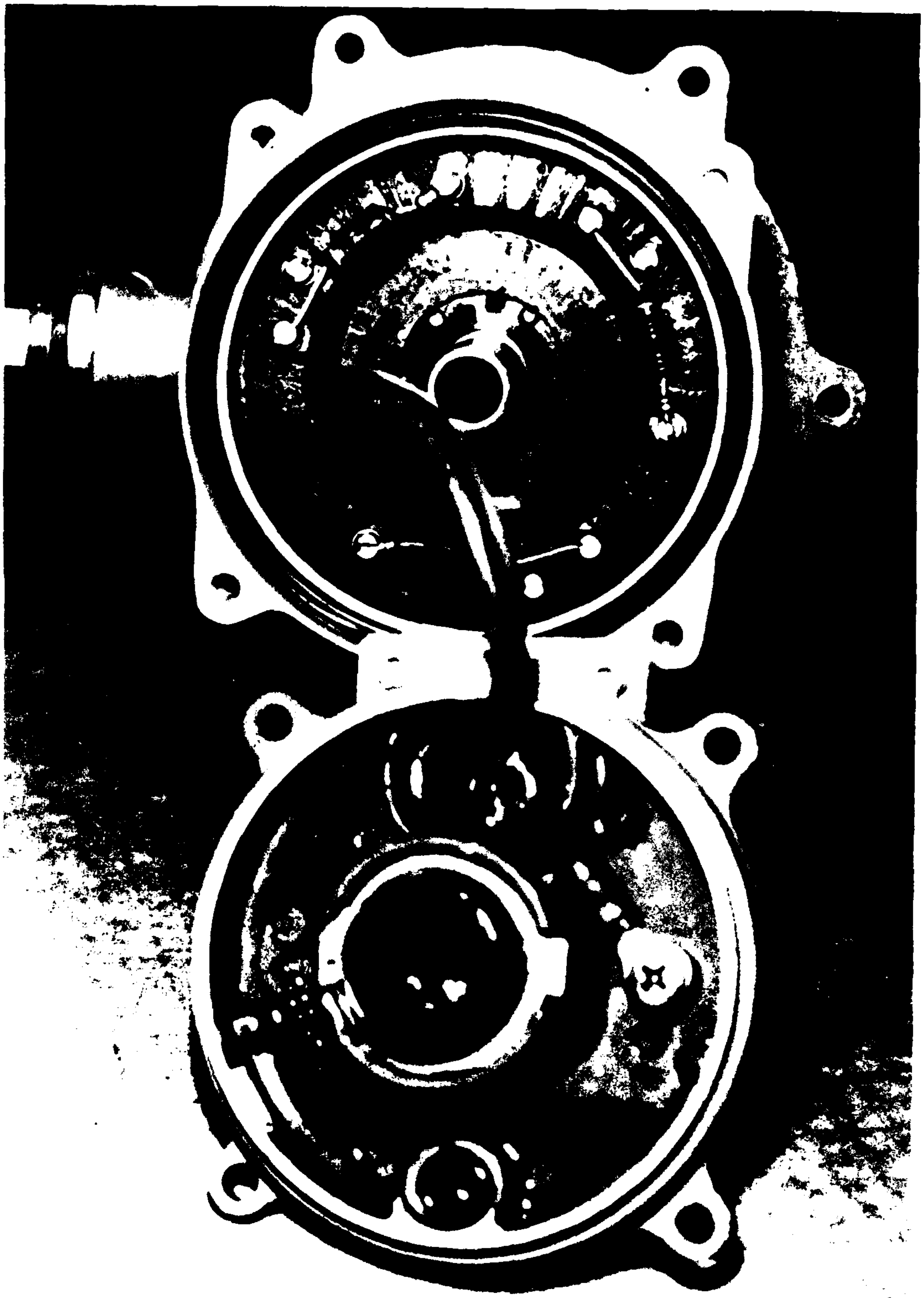


FIGURE 38. BOOST PUMP MOTOR FOLLOWING -40° AMK ENDURANCE TEST

TABLE 16. MANUFACTURER'S PERFORMANCE DATA (HYDRO-AIRE 60-703) OVERRIDE BOOST PUMP, 7/14/69

Flow Rate		Pressure	Voltage	Current amps			Power*	Fuel Temp	
(pph)	(gpm)	(psid)	(VAC)	φ1	φ2	φ3	(Watts)	(°F)	Test Conditions (JP4)
0	0	48.7	200	11.1	12.1	11.6	2890	75	JP-4 Specific Gravity 0.750 @ 75°F
5,000	13.3	47.3	200	11.6	12.5	12.1	3080	75	
10,000	26.6	46.0	200	12.0	13.2	12.4	3270	75	
20,000	53.3	42.8	200	13.3	14.3	13.8	3600	76	
30,000	79.9	39.5	200	14.0	15.2	14.1	3800	76	o fuel head maintained 10-15" above pump bellmouth
40,000	106.6	34.1	200	14.7	16.1	14.9	3950	76	o pump centerline 11.7 inches above inlet bellmouth
50,000	133.2	28.5	200	14.8	16.1	14.8	3970	76	
60,000	159.8	24.1	200	14.4	15.6	14.4	3855	76	

*Maximum allowable power = 4500 Watts

4.4 Boost Pump Performance Results

The boost pump performed satisfactorily with no significant increase in pump case temperature, pumping continuously (15 gpm) for 2-hour periods with ambient, -20°C, and -40°C AMK. Steady flow electrical power measurements are compared to Jet A requirements in table 17. These data show the pump power requirements for AMK are approximately the same as those needed to pump Jet A. This result is at variance with the measurements made on the main boost pump (section 3.3) which showed that the power required to pump AMK was 5 to 18 percent higher than that for Jet A. In fact the power for -40°C AMK in the endurance test was less than that required for Jet A at the same temperature. Reasons for this anomalous behavior may reside in the fact that the endurance tests were performed with an override boost pump (with which the 2000-gallon tank was equipped) which develops higher pressure and flow rate than the main airplane boost pump used in the simulator tests. However, both pumps are of similar design and it was anticipated that their performance characteristics would be similar. Normally, it would be expected that input power would increase with lower temperature and increasing viscosity, however the drag reducing characteristics of FM-9 could be the source of the anomaly between the pumps. Aside from these differences, the main conclusion which can be drawn from the boost pump tests is that the pump will operate satisfactorily with AMK, particularly at low fuel temperatures.

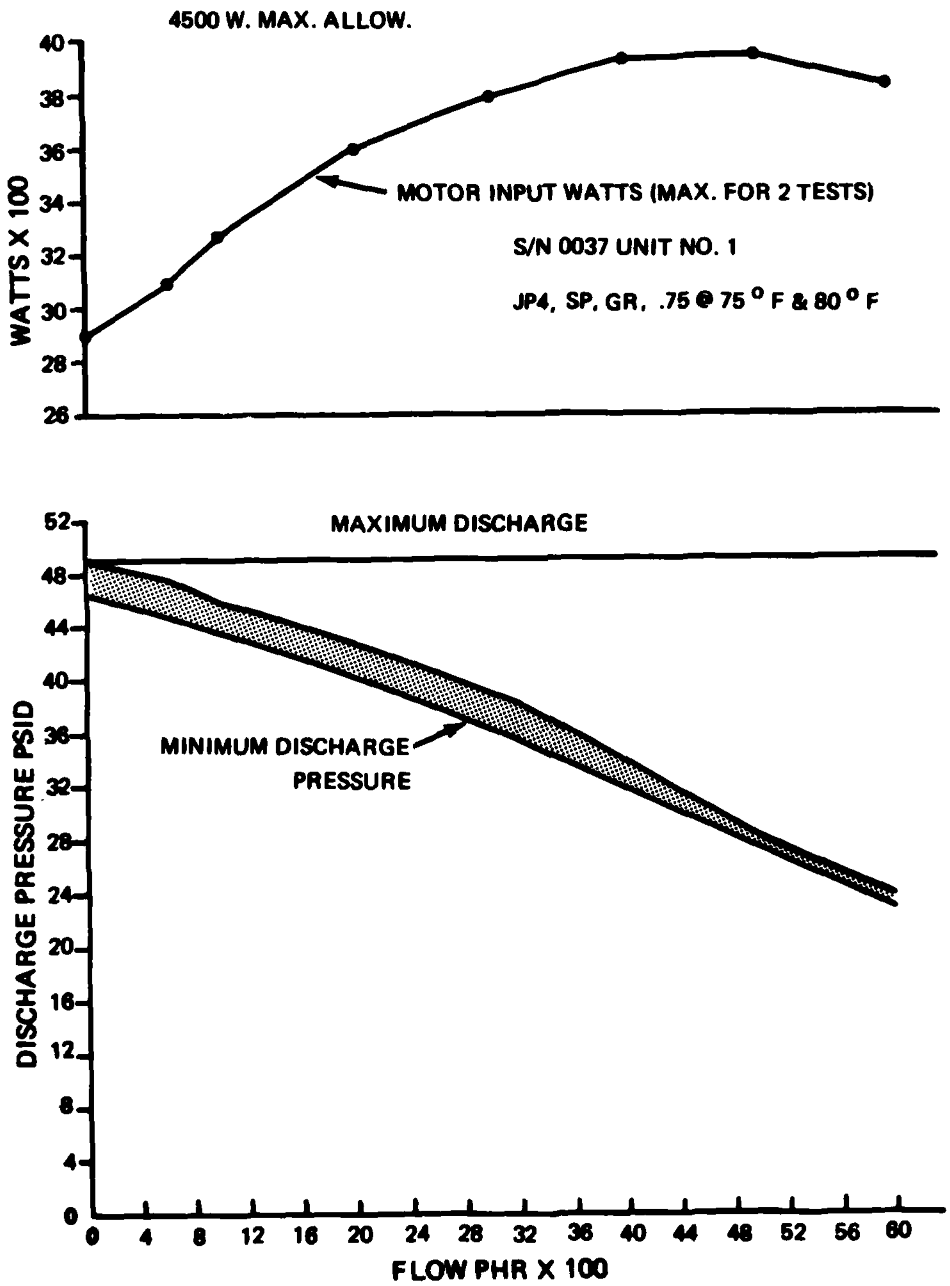


FIGURE 39. BOOST PUMP MANUFACTURERS CALIBRATION DATA

TABLE 17. RESULT OF BOOST PUMP POWER MEASUREMENTS
NOMINAL FLOW RATE = 15 GPM

Fuel	Temperature (^oC)	Flow (gpm)	Voltage (vac)	Current (amps)			Power*	
				$\phi 1$	$\phi 2$	$\phi 3$	(KW)	(HP)
	ambient	15.0	112.0	13.0	13.0	13.1	3.28	4.39
Jet A	-20	14.9	111.7	13.5	13.5	14.0	3.39	4.55
	-40	15.1	111.6	14.0	14.0	14.5	3.51	4.71
	ambient	15.0	111.5	13.0	13.0	13.0	3.22	4.32
AMK	-20	15.0	108.0	17.0	13.0	15.5	3.64	4.88
	-40	15.0	111.3	13.5	13.5	13.5	3.34	4.48

*Power factor = 0.741 (assumed from calibration test results)

During the boost pump endurance tests it was not possible to visually check for the presence of gel inside the tank. It is noted that when the boost pump was removed for inspection following the -20°C and -40°C endurance tests, it had warmed to ambient temperature and any gel which might have formed during the test could not be observed. Post-test inspections showed no unusual wear or deposits. The characterization data of samples obtained downstream from the boost pump (station S2) showed little evidence of degrading.

4.5 Degrader Performance Results

The degrader used in the endurance tests was comprised of a TF30 piston type fuel pump (which increased the test fuel pressure from about 20 psig to several thousand psig, depending on the temperature) and a high pressure throttling valve which dropped the pressure back down to a value below 50 psig. Under the very high shear rate conditions in the throttling valve, complete degrading of the AMK was expected. The FAA degrader design followed that of Mannheimer (reference 5) and the test device was intended as an experimental AMK degrader. AMK degradation was expected to be complete after one pass through the throttling valve. It was also expected that higher pressure differentials would be required to degrade AMK at lower temperatures, but the precise requirements were unknown. The fluid power versus temperature values used in these tests were specified by the FAA (table 18).

The degrader shaft torque and rpm were measured with a factory calibrated torque meter installed between the Varidrive and the pump (figure 40). The shaft power calculated from these measurements is included in table 18.

Flammability tests performed on the fuel samples collected downstream of the degrader throttling valve (station S3) showed the degrader restored the flammability to that of Jet A (table 15).

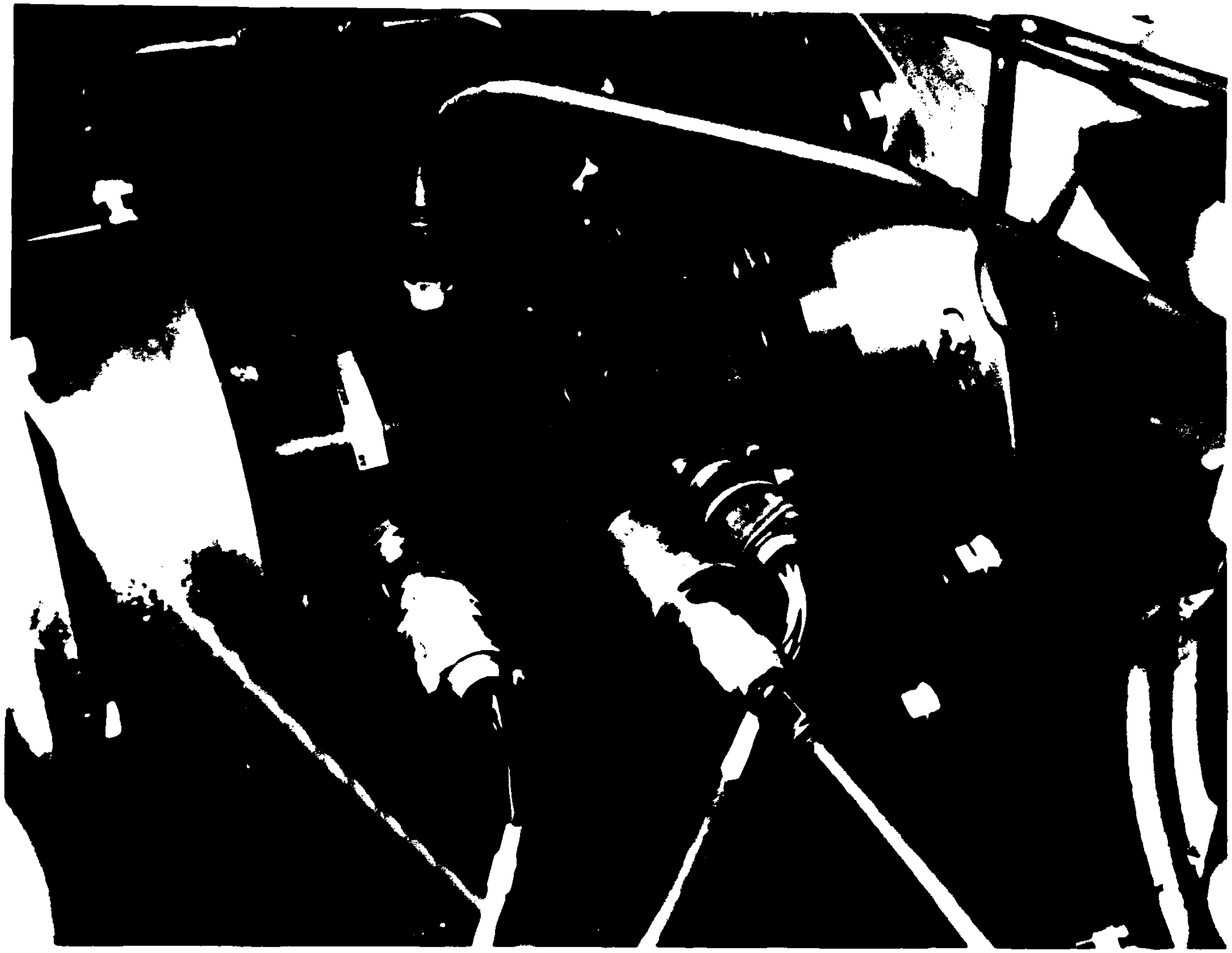


FIGURE 40. TYPICAL TORQUE METER INSTALLATION FOR DEGRADER PUMP AND ENGINE DRIVEN PUMP

TABLE 18. MEASUREMENTS OF AMK TEST DEGRADER POWER VERSUS TEMPERATURE USED IN ENDURANCE TESTS

Endurance Run	Flow Rate (gpm)	Fuel Temperature (°C)	Upstream Pressure (psig)	Delivered Power (HP)	Pump Pump Input Shaft Power (HP)
6	15.1	17	2252	19.8	25.0
7	14.9	-20	4115	35.8	41.6
9	14.8	-40	5622	48.5	54.8

4.6 Filter Performance Results

The flow performance of the following three filters was evaluated during the AMK endurance runs:

- o CF6-50 low pressure cartridge filter
- o JT-9D engine driven pump interstage filter
- o JT-8D fuel control wash filter

These filters, shown in figures 25, 41, and 42, were located downstream of the degrader throttling valve (figure 33) and were equipped with a bypass circuit in the event of excessive pressure drops. Baseline pressure drops through the filters were measured with Jet A prior to the AMK tests. After each run, the interstage (paper) filter was changed and the CF6 and JT-8D wash flow filters were cleaned with xylene-butanol solvent.

The pressure drop data for AMK (table 19) show slightly higher pressure drops in all filters at ambient temperature, and substantially higher pressure drops across the interstage and washflow filters at -20°C. The filters bypassed within a few minutes of operation with -40°C AMK fuel. Photographs of the filters immediately after the -40°C run (figures 43 to 45) showed large gel accumulations on the downstream side of all filters, explaining the pressure drop data. Gel was observed in all tests to cover the fine screen portion of the wash filter.

TABLE 19. STEADY FLOW FILTER PRESSURE DROPS (PSID)

Filter Type	Jet A			AMK		
	AMB	-20 C	-40 C	AMB	-20 C	-40 C
CF6 Filter	0.3 to 1.1	1.2	1.3	1.5 to 2.2	2.5 to 3.3	22.7
Engine Driven Pump Inter-Stage Filter	0.15 to 0.25	0.1 to 0.2	0.5	2.1 to 2.9	5.8 to 8.5	26.0
Fuel Control Wash Filter	1.0 to 2.0	1.9	2.5	0.2 to 1.9	58.8	70.3

FIGURE 41. CF6 -50 LOW PRESSURE CARTRIDGE FILTER

FIGURE 42. JT8-D WASH FLOW FILTER

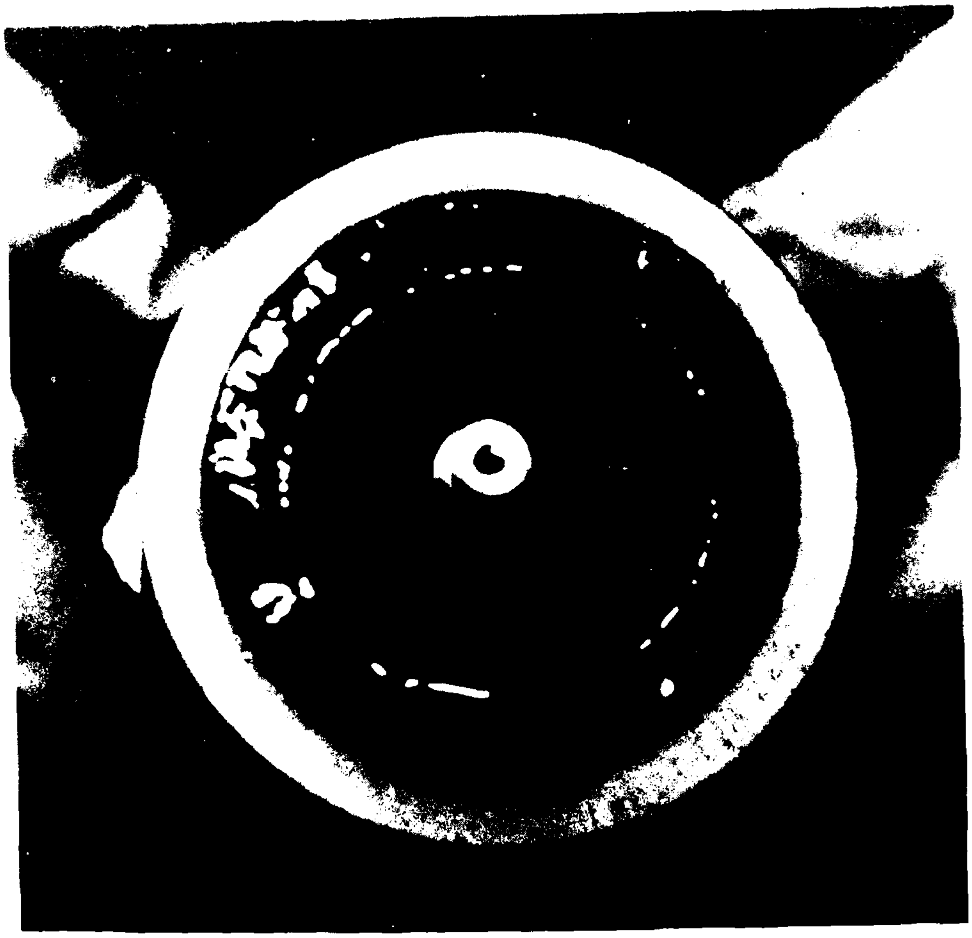


FIGURE 43. CF6 FILTER FOLLOWING -40°C AMK ENDURANCE TEST

FIGURE 44. JT9D ENGINE DRIVEN PUMP, INTERSTAGE FILTER FOLLOWING -40°C AMK ENDURANCE TEST

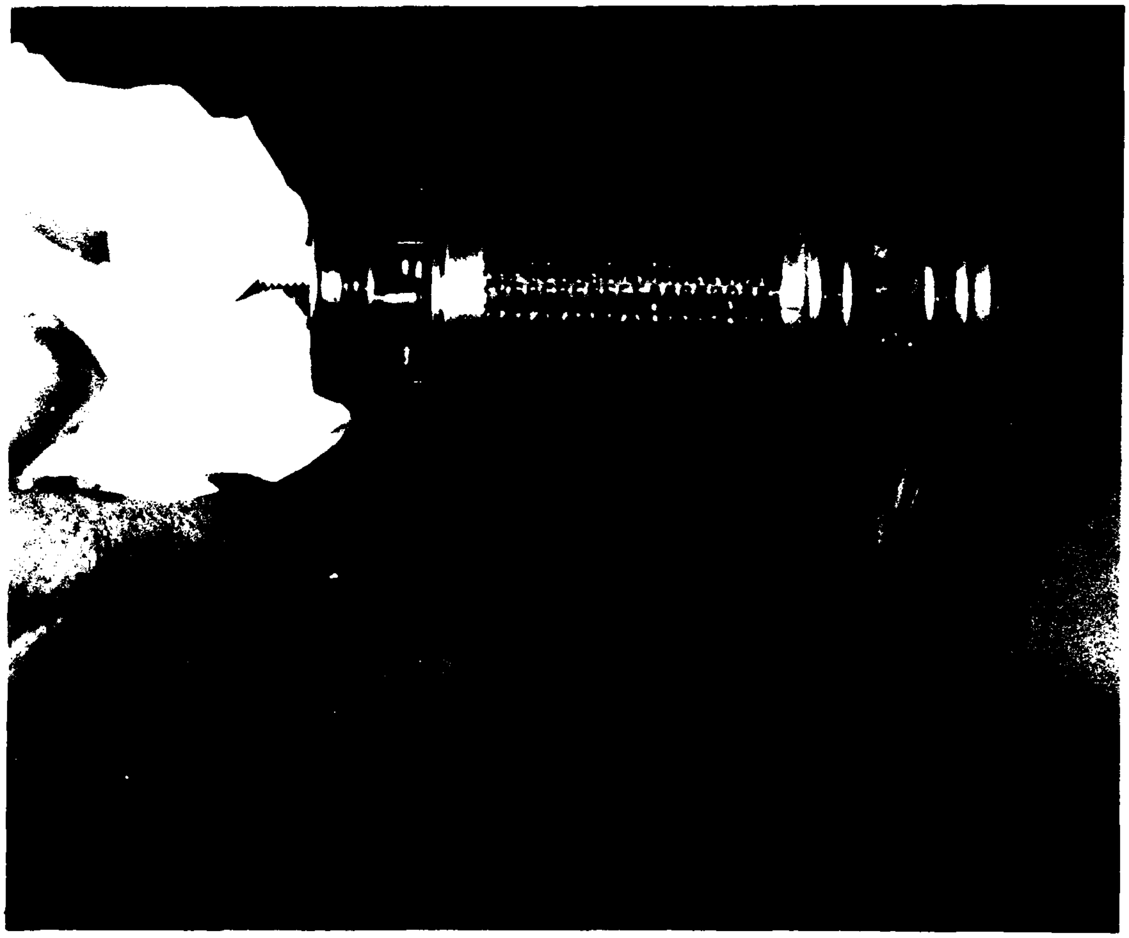


FIGURE 45. JT8-D FUEL CONTROL WASH FILTER FOLLOWING -40°C AMK ENDURANCE TEST

Following the AMK tests, repeat Jet A tests were performed which showed higher pressure drops than initially measured, specifically across the wash filter where the pressure drop was approximately six times higher.

Close-up photographs of the wash filter screen (figure 46) after the repeat Jet A tests showed evidence of gel deposits on the downstream side of the filter which persisted even after cleaning with xylene-butanol solvent.

4.7 Flow Measurement

The rate of fuel flow in the system from the supply tank through the pumps and filters was measured with a one-inch turbine flowmeter. This meter was installed in the system prior to the tests with Jet A and remained there during the three 2-hour endurance runs with AMK. The meter was expected to measure the AMK flow rate with sufficient accuracy for adjusting and monitoring purposes because it was located downstream of the degrader. A check of the meter flow rate with AMK was made by diverting the flow to a weigh tank while measuring the time required for a 200-lb increment. The agreement between the two methods was within 2.8 percent with the meter value being the lower of the two. Inspection of the meter after completion of all tests showed no unusual wear or deposits and the turbine rotated freely.

A 1/2-inch turbine flowmeter was installed in the fine-mesh outlet branch of the JT-8D wash filter prior to the -20°C endurance test with AMK. The purpose of this second meter was to measure the wash fuel flow, nominally set at 1.7 gpm. Because of formation of gel on the fine screen mesh, a high flow resistance resulted and the differential pressure caused the filter to bypass. During the AMK run at -40°C there was no indication of flow in the small meter. Subsequent inspection of the small meter showed that gel had collected inside the meter and prevented the turbine from rotating.

5. DISCUSSION

Results of the environmental and component performance tests revealed no insurmountable problems with airframe fuel system components operated with AMK over the temperature range and number of cycles studied. Problems were observed with airframe suction feed, and jet pump performance, and with engine fuel filters. The suction feed problem relates to an emergency operating capability which is an FAA service writing certification requirement and the engine fuel filter problem to degrader development and filter design. The latter problem is not in Boeing's purview. These and other relevant observations are briefly discussed in this section.

5.1 Airframe Component Functions

The suction feed results with ambient and -20°C AMK are of the most concern, since satisfactory feed system performance could not be demonstrated above 30,000 feet. In suction feed tests performed by Ching and Peacock, Jet A fuel met the required system flow and pressure to the maximum certified altitude (42,000 ft), but with ambient AMK the system was limited to 31,000 ft. This result is simuliar to the results of the Boeing tests. It is pointed out that these tests were performed without a degrader installed upstream of the engine driven pump which might or might not affect the suction feed capability. It is also noted that FAA certification requirements are for suction feed to the

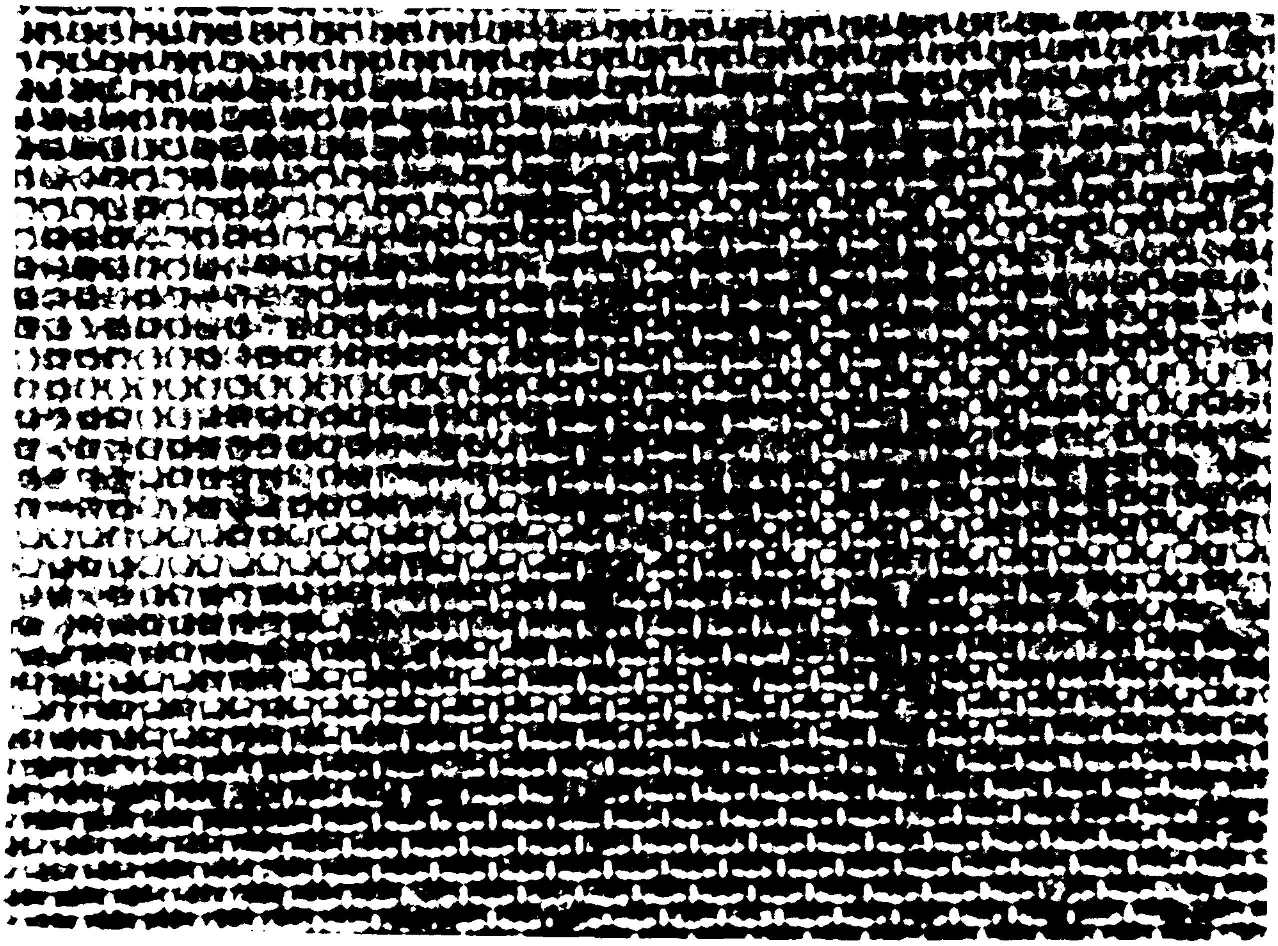


FIGURE 46. FINE MESH GEL RESIDUE AFTER CLEANING

airplane service ceiling and for engine restart on suction feed. The ability of a windmilling engine to drive a degrader and still maintain starting rpm is an open issue.

The B747 override boost pump, which is similar to the main B747 boost pump, showed no evidence of overheating when operated at various temperatures and at a cruise flow rate (15 gpm) for a two-hour period. Power measurements at steady flow conditions with AMK at ambient, -20°C, and -40°C were roughly the same as those for Jet A at the same temperatures. These findings are at odds with power measurements performed during short term operations with a main boost pump where 5 to 18 percent more power was needed to pump AMK than Jet A. This anomaly may arise from the fact that the override pump is designed for higher pressure and flow rate and at 15 gpm was operating further below its design flowrate than the main boost pump. With AMK the required pump power tended to decrease as the fuel temperature was reduced, whereas with Jet A the opposite trend was observed. This result may be due to the "flow improver" qualities of the FM-9 polymer.

Jet pump performance with AMK was substantially less than that with Jet A, except at -40°C. The AMK motive flow in these tests was presumably "undegraded" since the boost pump provides very little degrading. In a jet pump, the induced flow is a result of the low pressure produced by acceleration of the motive flow through the primary nozzle. The results suggest that the expansion process with AMK is quite different than that with Jet A at ambient temperature and -20°C. For a more complete understanding, experiments aimed at studying this expansion process with AMK in more detail would be required. It should also be pointed out that the above performance tests were conducted with fuel not saturated with water. It might be informative to study the effects of controlled amounts of water in the induced flow on the jet pump performance.

The gauging data and environmental test data indicate that AMK will behave in a fashion similar to Jet A inside the fuel tank. There was no evidence of gel buildup or blockage of the fuel transfer holes (mouse holes) cut in the bottom stringers in the simulator tank.

5.2 Gel Formation in Engine Filters

During the 2-hour engine feed simulation tests, the interior of the feed tank could not be viewed and it is not known whether gel was formed inside the tank. However, the only gel formations observed in any component of the feed system were downstream of the filters; it is believed that this gel was formed as the fuel flowed through the filters, and did not originate in the fuel tank. Some or all of the filters are found in various engine feed systems, and their sensitivity to gel formation is in all probability a function of the AMK degrading unit performance. It appears that the degrader used in these studies was inadequate for filter performance, although the degraded fuel had satisfactory flammability characteristics.

The tendency of gel to build up and eventually cause filters to bypass was found only at the low temperatures (-20°C and -40°C); the time to bypass decreased as temperature decreased. There were semi-permanent gel deposits on the fine screen portion of the fuel control wash filter which could not be totally removed with the cleaning techniques used. Either more effective degrading or a change in filtration approach appears necessary to solve this filter performance problem.

5.3 Heat Transfer Considerations

The thermal response of AMK when subjected to low temperature environments was essentially the same as that for Jet A. This result is important for the analysis of buoyantly driven (free convection) heat transfer, since existing analytical models developed for standard jet fuel may also be applied to the same systems operating with AMK. This finding is contrary to that for forced convection, where AMK is a less effective heat transfer medium. Details of the freezing/thawing process (i.e., low temperature flowability) of AMK at temperatures near or below the freezing point were not observed in this program.

5.4 Gel and String Formation

The gels observed at low temperatures (-20°C and lower) during boost pump operation in the simulator tank were mainly attributed to shearing of AMK at the boost pump vapor removal line exit. These gel formations floated on the free surface of the fuel, disappearing as bulk fuel temperatures approached ambient, and did not appear to affect the operation of the boost pump in any way.

The formation of the "strings" observed during the thermal cycling tests may have been produced by shearing action associated with natural convection during warming, however, reasons why the strings formed only during the warm-up phase of the cycle are not clear. The strings were small, dissolved at higher temperatures, and did not present any problems in these fuel system tests. Neither the gels nor the strings were observed to be ingested into the boost pump so their effect on downstream components in the fuel system cannot be judged.

5.5 Flowability of AMK

The boost pump, jet pump, and suction feed component tests showed that flowability of AMK improves with decreasing temperature, and that AMK flowability is better than Jet A in the vicinity of -40°C. This result is attributed to the presence of the FM-9 polymer which apparently acts as a flow improver.

6. CONCLUSIONS

The component and system tests performed in this program were not of sufficient duration or generality to determine whether Boeing airframe fuel systems could operate satisfactorily with AMK fuel. As to the engine fuel system, only the main fuel pump and representative filters were tested; in general, reliance should be placed on separate engine studies to determine AMK fuel suitability in engine fuel systems.

It was concluded that

- Water vapor ingestion in amounts that would be expected in worst case airline service (≈200 ppm) does not appear to cause special problems with AMK.
- Existing heat transfer calculation methods can be used to calculate fuel temperatures in fuel tanks.

- Capacitance fuel gauge systems are compatible with AMK fuel which did not contain gel.

- Antimisting properties of AMK are not adversly affected by low temperature exposures, or by normal airplane shock and vibration exposure.

However, drawing from the results of fuel system environmental and component tests of AMK, the following list indicates concerns which Boeing feels must be resolved before general fleet use of AMK is considered practical.

- Introduction of improperly blended AMK (such as that inadvertently produced during in-line blending in this program) into an airplane fuel tank would be unacceptable to airplane performance.

- A degrader whose performance is substantially better than the experimental degrader of this program or filter modification will be required to avoid blockage of the engine filters.

- Jet pump performance is poor with AMK

- If main boost pump power requirements are higher with AMK, the increased power requirement would substantially affect boost pump thermal protection.

- The altitude at which adequate suction feed (boost pump off) performance could be maintained was some 5000 feet lower with AMK than with Jet A (except at very cold fuel temperatures) and would cause the airplane service ceiling to be similarly reduced.

7. REFERENCES

1. Klueg, E., 6th U.S./U.K. Technical Committee Meeting on Antimisting Fuel, March 1980.

2. Botteri, B. P., et. al., Aircraft Fire Safety Vol. 2. AGARD Advisory Report No. 132, November (1979).

3. Grenich, A. F., Experimental Study of Jet Fuels Treated with the Antimisting Additive FM-9, D6-48030TN, Boeing Commercial Airplane Company, November 1978.

4. Grenich, A. F., Burning Tests of Fuel with FM-9 Antimisting Additive, D6-48042TN, Boeing Commercial Airplane Company, December 1978.

5. Mannheimer R. J., Degradation and Characterization of Antimisting Kerosene (AMK), DOT/FAA/CT-82/93.

6. Coffinberry, George, Antimisting Fuel Degrader Investigation, DO/FAA/CT-82/72.

7. Ching, F. Y. and Peacock A. T., Compatibility Study of Antimisting Kerosene and the DC-10/KC-10 Fuel System, DOT/FAA/CT-82/116 (1983).

8. Fiorentino A. J. and Planell J. R., An Assessment of the Use of Antimisting Fuel in Turbofan Engines, NASA CR 168081 (1983).

9. Pasion, A. J., In-Flight Fuel Tank Temperature Survey Data, NASA CR-159569, 1979.

10. Byrne D. V., An Experimental Study of Fuels, Near or Below Their Freezing Point, Boeing Document, D6-48572, (1979).

11. McConnell P. M., Massmann L. A., Peterson G. N., Fuel/Engine/Airframe Trade-Off Study Operational Effects of Increased Freeze Point Fuels, AFWAL-TR-82-2067 (1982).

12. Desmarais L. A. and Tolle F. F., Fuel Freeze Point Investigations, AFWAL-TR-84-XXXX, (to be published).

13. McConnell P. M., Desmarais L. A., Tolle F. F., Heat Transfer in Airplane Fuel Tanks at Low Temperatures, ASME Paper No. 83-HT-102,

14. Yavrouran A. H., Sarboluki M., Sarohia V., Influence of Liquid Water and Water Vapor on Antimisting Kerosens (AMK), DOT/FAA/CT-82/18, (1983).

15. Grantham D. D. and Sissenwine N., High Humidity Extremes in the Upper Air, AFCAL-70-0563 (1970).

16. Sissenwine, N. and Cormier, R. V., Synopsis of Background Material for MIL-STD-210B Climatic Extremes for Military Equipment, AFCRL-TR-74-0052, Bedford, Massachusetts, 24 January 1974.

8. NOMENCLATURE

AMK = antimisting kerosene
c = concentration
Cp = Specific heat at constant pressure
Cv = Specific heat at constant volume
C = constant
D = diameter
FAA = Federal Aviation Administration
h = height
m = total mass
M = Mach number
N = pressure ratio
p = pressure
Δp = differential pressure
Q = flow rate
R = recovery factor, gas constant
Re = Reynolds number
t = time
T = temperature
V = velocity
w = water density

Greek Symbols

γ = C_p/C_v
φ = entrainment ratio
η = efficiency
ρ = density

Subscripts

R = recovery
∞ = freestream
w = water
d = discharge
i = induced
m = motive
1 = pump discharge

APPENDIX A

TEST MATRIX

The environmental and component tests were performed in the sequence given in the following test matrix, table A-1. The number of tank tear-downs was minimized by combining certain test configurations, e.g., the boost pump and jet pump tests.

TABLE A-1. TEST MATRIX

RUN NO	TEST DESCRIPTION	TEST FUEL TYPE	CONTROLLED/SIMULATED PARAMETERS					FUEL TEMPERATURE			MEASUREMENTS							SAMPLE ANALYSIS (NO. OF SAMPLES)
			SLOSH & VIBRATION	PRESS. (ALTITUDE)	SKIN TEMPERATURE	FUEL WITHDRAWAL	HUMIDITY	START	INTERMEDIATE	END	THERMAL PROFILE	TANK PRESS.	FUEL LEVEL	GAUGE CAPACITANCE	FUEL REMOV. RATE	PHOTOGRAPHY	REMARK	
1	LOW TEMPERATURE DYNAMIC AND GAGING	NEAT JET A	YES	—	YES	YES	—	-10 °C	-40 °C	AMBIENT	YES	—	YES	YES	YES	IF FOUND NECESSARY		YES (3)
2	LOW TEMPERATURE DYNAMIC AND GAGING	NEAT JET A	YES	—	YES	YES	—	-10 °C	-20 °C	AMBIENT	YES	—	YES	YES	YES	IF FOUND NECESSARY		YES (2)
3	LOW TEMPERATURE DYNAMIC AND GAGING	NEAT JET A	YES	—	—	YES	—	AMBIENT	AMBIENT	AMBIENT	—	—	YES	YES	YES	—		YES (2)
4	LIQUID WATER/WATER VAPOR	NEAT JET A	YES	YES	YES	YES	YES	AMBIENT	-40 °C	AMBIENT	YES	YES	YES	YES	YES	YES		YES (3)
5	LOW TEMPERATURE DYNAMIC AND GAGING	AMK	YES	—	YES	YES	—	AMBIENT	-40 °C	AMBIENT	YES	—	YES	YES	YES	YES		YES (3)
6	LOW TEMPERATURE DYNAMIC AND GAGING	AMK	YES	—	YES	YES	—	AMBIENT	-20 °C	AMBIENT	YES	—	YES	YES	YES	YES		YES (3)
7	LOW TEMPERATURE DYNAMIC AND GAGING	AMK	YES	—	—	YES	—	AMBIENT	AMBIENT	AMBIENT	—	—	YES	YES	YES	—		YES (2)
8	THERMAL CYCLING 1ST CYCLE	AMK	YES	—	YES	—	—	AMBIENT	50 ° to -80 °C	AMBIENT	YES	—	—	—	—	1		YES (2)
9	THERMAL CYCLING 2ND CYCLE	AMK	YES	—	YES	—	—	AMBIENT	50 ° to -80 °C	AMBIENT	YES	—	—	—	—	1		YES (1)
10	THERMAL CYCLING 3RD CYCLE	AMK	YES	—	YES	—	—	AMBIENT	50 ° to -80 °C	AMBIENT	YES	—	—	—	—	1		YES (1)
11	THERMAL CYCLING 4TH CYCLE	AMK	YES	—	YES	—	—	AMBIENT	50 ° to -80 °C	AMBIENT	YES	—	—	—	—	1		YES (1)
12	THERMAL CYCLING 5TH CYCLE	AMK	YES	—	YES	—	—	AMBIENT	50 ° to -80 °C	AMBIENT	YES	—	—	—	—	1		YES (1)
13	LIQUID WATER/ WATER VAPOR 1ST CYCLE	AMK	YES	YES	YES	YES	YES	AMBIENT	-40 °C	AMBIENT	YES	YES	YES	YES	YES	YES		YES (3)

1 IF FUEL APPEARANCE CHANGES OR OTHER INTERESTING PHENOMENON IS OBSERVED

TABLE A-1. TEST MATRIX (CONTINUED)

RUN NO	TEST DESCRIPTION	TEST FUEL TYPE	CONTROLLED/SIMULATED PARAMETERS					FUEL TEMPERATURE			MEASUREMENTS							SAMPLE ANALYSIS
			SLOSH & VIBRATION	PRESS. (ALTITUDE)	SKIN TEMPERATURE	FUEL WITHDRAWAL	HUMIDITY	START	INTERMEDIATE	END	THERMAL PROFILE	TANK PRESS.	FUEL LEVEL	GAUGE CAPACITANCE	FUEL REMOV. RATE	PHOTOGRAPHY	REMARK	(NO. OF SAMPLES)
14	LIQUID WATER/ WATER VAPOR 2ND CYCLE	AMK	YES	YES	YES	YES	YES	AMBIENT	-40 °C	AMBIENT	YES	YES	YES	YES	YES	YES		YES (3)
15	LIQUID WATER/ WATER VAPOR 3RD CYCLE	AMK	YES	YES	YES	YES	YES	AMBIENT	-40 °C	AMBIENT	YES	YES	YES	YES	YES	YES		YES (3)
16	LIQUID WATER/ WATER VAPOR 4TH CYCLE	AMK	YES	YES	YES	YES	YES	AMBIENT	-40 °C	AMBIENT	YES	YES	YES	YES	YES	YES		YES (3)
17	SUCTION FEED PERFORMANCE AT 30,000'	NEAT JET A	—	YES	YES	YES	—	AMBIENT	-40 °C		YES	YES	YES	—	YES	—	2	
18	SUCTION FEED PERFORMANCE AT 35,000'	NEAT JET A	—	YES	YES	YES	—	AMBIENT	-40 °C		YES	YES	YES	—	YES	—	2	
19	SUNCTION FEED PERFORMANCE AT 40,000'	NEAT JET A	—	YES	YES	YES	—	AMBIENT	-40 °C		YES	YES	YES	—	YES	—	2	
20	SUCTION FEED PERFORMANCE AT 30,000'	NEAT JET A	—	YES	YES	YES	—	AMBIENT	-20 °C		YES	YES	YES	—	YES	—	2	
21	SUCTION FEED PERFORMANCE AT 35,000'	NEAT JET A	—	YES	YES	YES	—	AMBIENT	-20 °C		YES	YES	YES	—	YES	—	2	
22	SUCTION FEED PERFORMANCE AT 40,000'	NEAT JET A	—	YES	YES	YES	—	AMBIENT	-20 °C		YES	YES	YES	—	YES	—	2	
23	SUCTION FEED PERFORMANCE AT 30,000'	NEAT JET A	—	YES	—	YES	—	AMBIENT	AMBIENT		—	YES	YES	—	YES	—	2	
24	SUCTION FEED PERFORMANCE AT 35,000'	NEAT JET A	—	YES	—	YES	—	AMBIENT	AMBIENT		—	YES	YES	—	YES	—	2	

2 ALSO MEASURE ENGINE FEED LINE PRESSURE AND ENGINE PUMP DISCHARGE PRESSURE IN ALL SUCTION FEED TESTS

TABLE A-1. TEST MATRIX (CONTINUED)

RUN NO.	TEST DESCRIPTION	TEST FUEL TYPE	CONTROLLED/SIMULATED PARAMETERS					FUEL TEMPERATURE			MEASUREMENTS							SAMPLE ANALYSIS (NO. OF SAMPLES)
			SLOSH & VIBRATION	PRESS. (ALTITUDE)	SKIN TEMPERATURE	FUEL WITHDRAWAL	HUMIDITY	START	INTERMEDIATE	END	THERMAL PROFILE	TANK PRESS.	FUEL LEVEL	GAUGE CAPACITANCE	FUEL REMOV. RATE	PHOTOGRAPHY	REMARK	
25	SUCTION FEED PERFORMANCE AT 40,000'	NEAT JET A	—	YES	—	YES	—	AMBIENT	AMBIENT		—	YES	YES	—	YES	—	2	
26	SUCTION FEED PERFORMANCE AT 30,000'	AMK	—	YES	YES	YES	—	AMBIENT	-40° C		YES	YES	YES	—	YES	—	2	
27	SUCTION FEED PERFORMANCE AT 35,000'	AMK	—	YES	YES	YES	—	AMBIENT	-40° C		YES	YES	YES	—	YES	—	2	
28	SUCTION FEED PERFORMANCE AT 40,000'	AMK	—	YES	YES	YES	—	AMBIENT	-40° C		YES	YES	YES	—	YES	—	2	
29	SUCTION FEED PERFORMANCE AT 30,000'	AMK	—	YES	YES	YES	—	AMBIENT	-20° C		YES	YES	YES	—	YES	—	2	
30	SUNCTION FEED PERFORMANCE AT 35,000'	AMK	—	YES	YES	YES	—	AMBIENT	-20° C		YES	YES	YES	—	YES	—	2	
31	SUCTION FEED PERFORMANCE AT 40,000'	AMK			YES	YES	—	AMBIENT	-20° C		YES	YES	YES	—	YES	—	2	
32	SUCTION FEED PERFORMANCE AT 30,000'	AMK	—	YES	—	YES	—	AMBIENT	AMBIENT		—	YES	YES	—	YES	—	2	
33	SUCTION FEED PERFORMANCE AT 35,000'	AMK	—	YES	—	YES	—	AMBIENT	AMBIENT		—	YES	YES	—	YES	—	2	
34	SUCTION FEED PERFORMANCE AT 40,000'	AMK	—	YES	—	YES	—	AMBIENT	AMBIENT		—	YES	YES	—	YES	—	2	
35	BOOST PUMP MAXIMUM POWER	NEAT JET A			YES	YES		AMBIENT	-40° C		YES	YES	YES	—	YES	YES	3	YES (2)
36	BOOST PUMP CRUISE POWER	NEAT JET A			YES	YES		AMBIENT	-40° C		YES	YES	YES	—	YES	YES	3	YES (2)
37	BOOST PUMP DEAD HEAD	NEAT JET A			YES	YES		AMBIENT	-40° C		YES	YES	YES	—	YES	YES	3	YES (2)

2 ALSO MEASURE ENGINE FEED LINE PRESSURE AND ENGINE PUMP DISCHARGE PRESSURE IN ALL SUCTION FEED TESTS

3 ALSO MEASURE IN THESE RUNS • BOOST PUMP POWER INPUT • PUMP CASE TEMPERATURE • VAPOR REMOVAL FLOW RATE • PUMP DISCHARGE PRESSURE • JET PUMP FLOW RATE • JET PUMP DISCHARGE PRESSURE

TABLE A-1. TEST MATRIX (CONTINUED)

RUN NO	TEST DESCRIPTION	TEST FUEL TYPE	CONTROLLED/SIMULATED PARAMETERS: SLOSH & VIBRATION	PRESS. (ALTITUDE)	SKIN TEMPERATURE	FUEL WITHDRAWAL	HUMIDITY	FUEL TEMPERATURE: START	INTERMEDIATE	END	MEASUREMENTS: THERMAL PROFILE	TANK PRESS.	FUEL LEVEL	GAUGE CAPACITANCE	FUEL REMOV. RATE	PHOTOGRAPHY	REMARK	SAMPLE ANALYSIS (NO. OF SAMPLES)
38	BOOST PUMP JET PUMP	NEAT JET A			YES	YES		AMBIENT	-40 °C		YES	YES	YES	—	YES	YES	△3	YES (1)
39	BOOST PUMP MAXIMUM POWER	NEAT JET A			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	△3	YES (2)
40	BOOST PUMP CRUISE POWER	NEAT JET A			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	△3	YES (2)
41	BOOST PUMP DEAD HEAD	NEAT JET A			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	△3	YES (2)
42	BOOST PUMP JET PUMP	NEAT JET A			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	△3	YES (1)
43	BOOST PUMP MAXIMUM POWER	NEAT JET A			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	△3	YES (2)
44	BOOST PUMP CRUISE POWER	NEAT JET A			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	△3	YES (2)
45	BOOST PUMP DEAD HEAD	NEAT JET A			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	△3	YES (2)
46	BOOST PUMP JET PUMP	NEAT JET A			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	△3	YES (1)
47	BOOST PUMP MAXIMUM POWER	AMK			YES	YES		AMBIENT	-40 °C		YES	YES	YES	—	YES	YES	△3	YES (2)
48	BOOST PUMP CRUISE POWER	AMK			YES	YES		AMBIENT	-40 °C		YES	YES	YES	—	YES	YES	△3	YES (2)

△3 ALSO MEASURE IN THESE RUNS • BOOST PUMP POWER INPUT • PUMP CASE TEMPERATURE • VAPOR REMOVAL FLOW RATE • PUMP DISCHARGE PRESSURE • JET PUMP FLOW RATE • JET PUMP DISCHARGE PRESSURE

TABLE A-1. TEST MATRIX (CONCLUDED)

RUN NO	TEST DESCRIPTION	TEST FUEL TYPE	CONTROLLED/SIMULATED PARAMETERS					FUEL TEMPERATURE			MEASUREMENTS							SAMPLE ANALYSIS
			SLOSH & VIBRATION	PRESS (ALTITUDE)	SKIN TEMPERATURE	FUEL WITHDRAWAL	HUMIDITY	START	INTERMEDIATE	END	THERMAL PROFILE	TANK PRESS.	FUEL LEVEL	GAUGE CAPACITANCE	FUEL REMOV. RATE	PHOTOGRAPHY	REMARK	(NO. OF SAMPLES)
49	BOOST PUMP DEAD HEAD	AMK			YES	YES		AMBIENT	-40 °C		YES	YES	YES	—	YES	YES	3	YES (2)
50	BOOST PUMP JET PUMP	AMK			YES	YES		AMBIENT	-40 °C		YES	YES	YES	—	YES	YES	3	YES (1)
51	BOOST PUMP MAXIMUM POWER	AMK			YES	YES		AMBIENT	-30 °C		YES	YES	YES	—	YES	YES	3	YES (2)
52	BOOST PUMP CRUISE POWER	AMK			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	3	YES (2)
53	BOOST PUMP DEAD HEAD	AMK			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	3	YES (2)
54	BOOST PUMP JET POWER	AMK			YES	YES		AMBIENT	-20 °C		YES	YES	YES	—	YES	YES	3	YES (1)
55	BOOST PUMP MAXIMUM POWER	AMK			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	3	YES (2)
56	BOOST PUMP CRUISE POWER	AMK			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	3	YES (2)
57	BOOST PUMP DEAD HEAD	AMK			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	3	YES (2)
58	BOOST PUMP JET PUMP	AMK			—	YES		AMBIENT	AMBIENT		—	YES	YES	—	YES	YES	3	YES (1)

3 ALSO MEASURE IN THESE RUNS • BOOST PUMP POWER INPUT • PUMP CASE TEMPERATURE • VAPOR REMOVAL FLOW RATE • PUMP DISCHARGE PRESSURE • JET PUMP FLOW RATE • JET PUMP DISCHARGE PRESSURE

APPENDIX B LIST OF TEST EQUIPMENT

1. Flammability Comparison Test Apparatus (FCTA)
   Serial No. 3
   Stock No. 4210-00-NA2-7799
   ID No. NAFEC 94266
   Includes: Log Book and Calibration Curve

2. Radiometer (for Item 1)
   Model No. C-1300-A-05-072
   Serial No. 79341
   Tag I.D. HY-CAL-ENG

3 Orifice Flow Cup
   Markings: A79050S4
   BS-1758-1953

4. Filter Ratio Tester
   Identification: None

   304L Stainless Steel Filter Screen
   Twirled Dutch Weave (CEBO)
   Metal Filter Cloth (165 x 1400 Mesh)
   Purchased from Tetko Inc., Monterey Park, CA

5. Turbine Flowmeter (1-inch), 0-50 gpm
   Fischer and Porter Model 10C1510A
   Mfr's S/N 6911A1411A9

6. Turbine Flowmeter (1/2 inch), 0-10 gpm
   Fischer and Porter Model 10C1510A
   Mfr's S/N 8103A0490A6

7. Varidrive - 35 HP, U. S. Electrical Motor Co.
   L. A. Calif. or Medford Conn
   60 CPS, 1200 rpm 220V or 440 V
   Gear Ratio 6.7

8. Varidrive - 75 HP

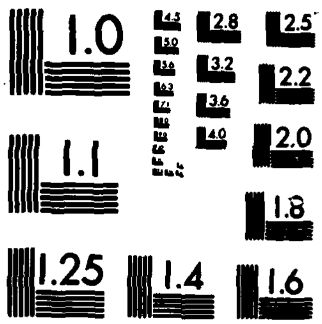
9. Capacitance Gage - Mfg. Simmons Precision
   (Gage Fuel Transmitter) Part # 391 046-172
   Spec. No. 10-605-20-4

10. Humidity Probe - Scientific Thunder
    Model PC-2100

11. Jet Pump - Allen Aircraft Products
    Model 68E108

12. JT-9D Engine Driven Pump

AD-A150 825 AIRCRAFT WING FUEL TANK ENVIRONMENTAL SIMULATOR TESTS 2/2
FOR EVALUATION OF A..(U) BOEING MILITARY AIRPLANE CO
SEATTLE WA P M MCCONNELL ET AL. OCT 84
UNCLASSIFIED DOT/FAA/CT-84/15 DTFA03-83-00038 F/G 13/11 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

13. Degrader Pump

14. Degrader Throttling Valve

15. In-Line-Blending Unit 5 gpm, 25 gpm FAA Furnished

16. Torque Meter

17. CF6 Low Pressure, Cartridge Filter
    (FAA Furnished)

18. Flow Control, Nozzle Wash Filter
    (FAA Furnished)

APPENDIX C
DETERMINATION OF WATER CONTENT OF ANTIMISTING KEROSENE FUEL

The water content of AMK fuel samples was determined using an automatic coulometric titrator, the Aquatest IV. This instrument, manufactured by Photovolt Corporation of New York, N.Y., generates electrolytically the exact quantity of Karl Fischer reagent required for the titration. Because one coulomb of electricity is equivalent to 186.53 micrograms of water, the necessity for standardized calibration is eliminated.

Due to the nature of the AMK samples several approaches were used in the initial stages to optimize the procedure. One approach used to reduce the possible effect of AMK additives on the electrodes was to add a solvent, chloroform, to the titration vessel to increase the solution volume. Another method tried was to use extra titration vessel solution. The actual procedure selected was to add extra titration solution to the vessel and to change the solution more frequently than the instruction manual recommends.

To conduct the tests, the Aquatest IV was conditioned as described in the operating instruction manual and then an aliquot of AMK fuel was injected into the titration vessel, through the septum, using a hypodermic syringe. When the Karl Fischer reaction was complete, the number of coulombs used was translated into micrograms of water and this value displayed on the instrument digital readout as micrograms, ppm, or percent water as selected.

APPENDIX D

IN-LINE BLENDING EXPERIENCE

(see pages 27-31)

APPENDIX D

In-Line Blending Experience

The in-line blender, developed by the FAA, and several 40-pound buckets of FM-9™ slurry were provided to produce the test AMK used for the component tests. The unit, designed to meet explosion-proof specifications, required 230V, 3 phase, 25 amp power. During the initial setup and blending operations the FAA provided an experienced engineer to train Boeing test personnel. Initially some problems were experienced with the blender operation, resulting in AMK which contained less FM-9 than desired and in which some separation of the polymer was observed as a result of poor mixing. These problems were resolved and subsequent blends (of the amount of 6,000 gallons) were performed satisfactorily. Details of this experience are reported here since it was the first attempt to use an in-line blender to produce quantities of AMK, and as such may give guidance to others working on AMK test programs.

The blender was designed to operate at two nominal flow rates, 5 gpm and 25 gpm, and required calibration of the FM-9 slurry pump flow rate for each batch of AMK blended. The actual blending process between the Jet A and slurry takes place inside a 1-inch diameter static mixing tube approximately 15 inches long mounted horizontally on the unit. A diaphragm type metering pump contained with the blender provided the Jet A flow at 5 gpm; a recalibration of this pump was not required for each run. For the high flow rate blending (25 gpm), a separate pressurized source (e.g. tanker truck) of Jet A was required. Prior to the blending startup, the slurry (FM-9) must be homogenized. Initially this was accomplished by hand, requiring one to two hours of time. Subsequently, this time was reduced to approximately 20 minutes with the use of a mechanical mixer (aluminum paddle blade coupled to a drill motor) (figures D-1 and D-2).

Characterization tests on samples taken prior to each component test run incuded orifice cup, filter ratio, FCTA, and solids content. The orifice cup and filter ratio tests were performed approximately 30 minutes to one hour after blending while the solids content and FCTA tests were performed several days after blending. The solids content tests, performed in accordance with ASTM D381 procedures, are time consuming and expensive. Therefore, they were used to spot check the blending operations and were not performed on every sample. For the initial blends the orifice cup, filter ratio, and flammability test results were all within the limits established by the FAA. However, the solids content of two samples (1 and 2) was substantially lower than expected, but because the Jet A pump was out of calibration, this was not discovered until other mechanical problems began to develop with the pump.

During the first series of test runs (Runs 26-34), the diaphragm pump used to supply Jet A to the blender failed twice, apparently due to a malfunctioning check valve in the discharge. A check of this pump after the check valve was repaired showed that the pump produced flow rates which were 15 percent high in the 3 to 5 gpm range; in addition, the flow rate was not repeatable from run to run. The problems with the FAA's Jet A blender pump could not be satisfactorily resolved within the time constraints of the test schedule and a Boeing fuel pump with a turbine flow meter in the discharge line was substituted.

A Jet A flow rate of 3 gpm was selected for blending since the substitute pump would not produce good steady flow performance at higher flows. However, despite very careful calibration of both the Jet A pump and slurry pump, the

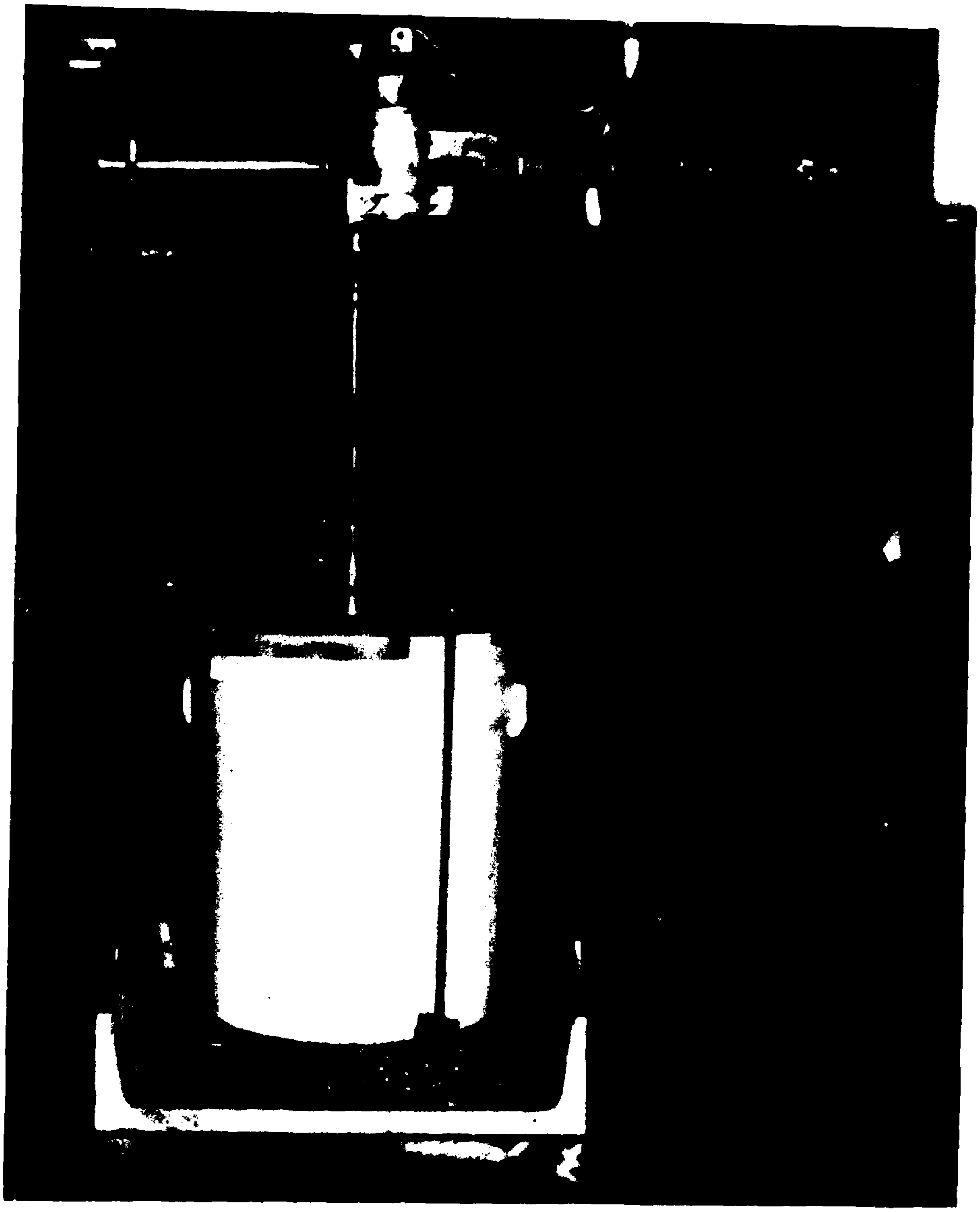


FIGURE D-1. ARANGEMENT FOR STIRRING SLURRY

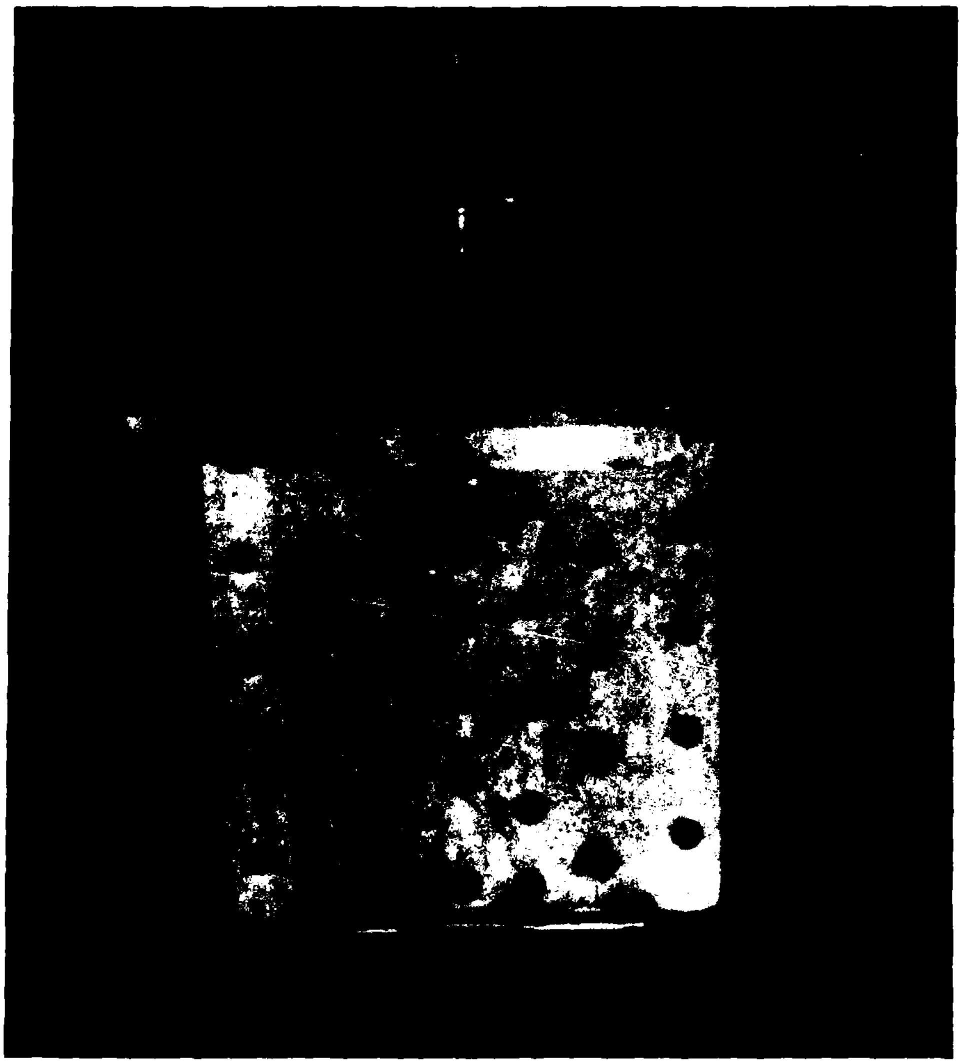


FIGURE D-2. MIXER PADDLE BLADE

solid content test on a sample of freshly blended fuel showed only weight 0.25 percent of polymer content when weight 0.3 percent was anticipated. Bits of slurry or gel were observed occasionally to pass through the transparent tube downstream of the blender, although the fuel appeared clear when loaded into the simulator tank. After a few blending operations on different days, a thick white mass, presumably undissolved slurry, was observed in the connecting tube during the transfer of AMK from the weigh tank to the test tank. The test run was stopped and the FAA was alerted to the problem; this white material was removed and photographed (figure D-3). When the simulator tank was refilled, it appeared clear after five minutes and the test was resumed. The next day, however, deposits of white material and gel were observed inside the tank and the gravity drain outlet was clogged. The tank was emptied with considerable difficulty. Inspection of the intermediate (weigh) tank showed gross deposits of unmixed slurry (totaling about 30 lbs) plated over the interior surface. It was first suspected that contamination of the fuel by water in the weigh tank was the cause of the problem. However, this possibility was ruled out after performing a simple test of mixing water with clear, freshly mixed AMK fuel in a beaker. The appearance of the gel in this test was completely different than the formations found in the tank. Assessment of the various events and observations indicated that the FM-9 slurry did not mix uniformly in the blender, and later separated, resulting in the buildup of deposits on weigh tank surfaces. Only after it had reached a level that allowed it to come out through the transparent drain line to the simulator tank was it detected.

This problem was apparently not unique to the Boeing operation. Subsequent discussions with the FAA revealed that separation of the slurry from the base fuel had also been observed by the FAA, although on a lesser scale, and had been attributed to unsatisfactory mixing.

The weigh tank, simulator tank, and interconnecting lines were flushed with the cleaning solvent recommended by the FAA (75 percent xylene, 25 percent butanol). The static mixing tube and the slurry pump were also disassembled and inspected at this time. The mixing tube was found to be contaminated with the same material, (figures D-4 and D-5). It was found that although the recommended solvent material was effective in removing the polymer accumulations, it reacted with Tygon tubing, the Lexan simulator tank windows, and the weigh tank sight tube, all of which had to be replaced. The solvent use should be restricted to metal and glass, and should not be used on seals, plastics, etc.

The problems experienced with poor mixing of the slurry and Jet A base fuel, were attributed to a combination of mixing tube design and the low blending flow rate necessary with the substitute Jet A pump. The static mixing tube which originally came with the unit was replaced by the FAA, and a larger Jet A pump (7gpm) was obtained. The FAA provided assistance in exchanging blender mixing tubes and in blending a trial batch of AMK. Prior to blending, the slurry was strained through a fine wire mesh screen (window screen) to remove any large chunks of slurry. This step may be unnecessary, however, since pre-mixing the slurry for at least 20 minutes using the mechanical mixer always provided a "chunk-free" source of slurry for blending.

Subsequent to blending the above trial batch, the slurry pump failed to pump. The pump stator, which is lined with a black rubber material, was found to be worn beyond acceptable limits. A new stator was ordered from the slurry pump

FIGURE D-3. RESIDUE FROM IMPROPERLY MIXED AMK

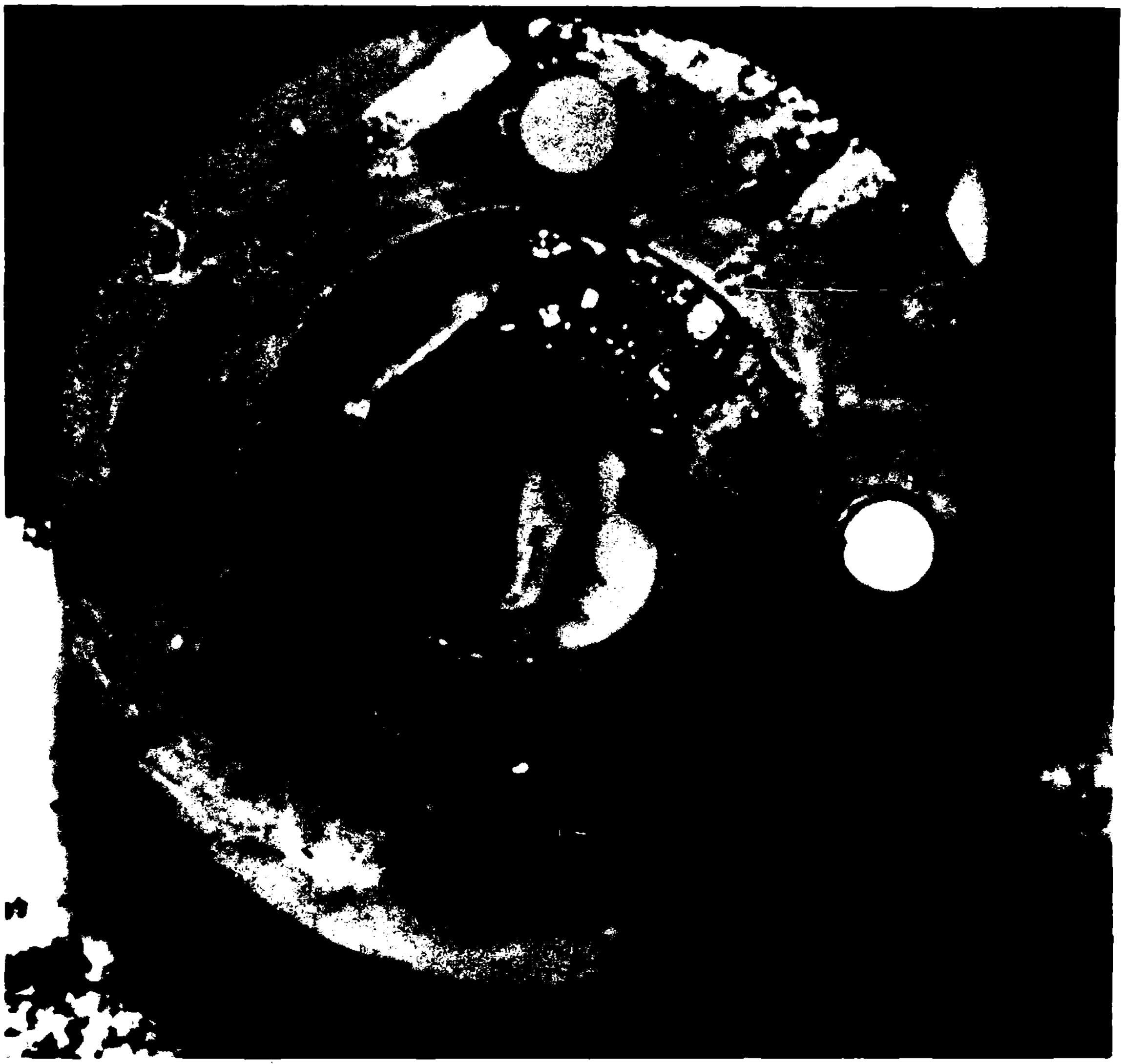


FIGURE D-4. RESIDUE IN STATIC MIXING TUBE

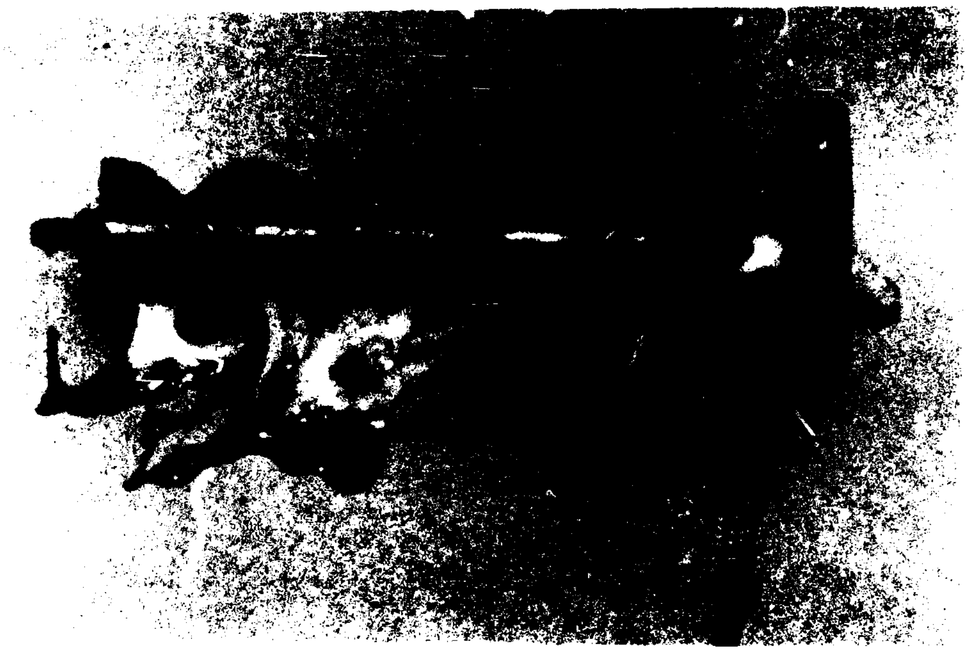


FIGURE D-5. RESIDUE ON STATIC MIXING TUBE VANES

manufacturer and installed in the slurry pump by the local manufacturer's field engineer. The pump was filled with slurry and performed normally.

The in-line blender was in this configuration used to produce good quality AMK test fuel for the remainder of the boost pump/jet pump component tests, for each cycle of the repeated water vapor ingestion tests, and the boost pump endurace tests (three batches, approximately 2000 gallons per batch).

END

FILMED

4-85

DTIC